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3000-HP ROLLER GEAR TRANSMISSION DEVELOPMENT PROGRAM. VOLUME V AIRCRAFT TIEDOWN TESTING

G. F. Gardner, et al

United Technologies Corporation

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3000-HP ROLLER GEAR TRANSMISSION DEVELOPMENT PROGRAM
Volume V - Aircraft Tiedown Testing

Sikorsky Aircraft
Division of United Technologies Corporation
Stratford, Conn. 06602

July 1975

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EUSTIS DIRECTORATE
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153

EUSTIS DIRECTORATE POSITION STATEMENT

This report is one of six volumes of the final report under this contract. The objective of this program is to conduct research on the feasibility of a high-reduction-ratio roller gear transmission of 3000 horsepower. This report covers the aircraft tiedown testing of the roller gear transmission. The roller gear tranmission successfully completed to 50-hour tiedown test; however, posttest ultrasonic inspection showed cracks in the second-row pinion rollers, emanating from the root of the electron beam welds. The grease-lubricated tail and intermediate gearboxes piggybacked on this program as an economy measure performed satisfactorily. In the interest of safety, the aircraft flight tests were deleted and replaced by redesign and fabrication of modified hardware for reliability bench testing.

The technical monitor for this contract was Mr. James Gomez, Technology Application Division.

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This report presents the results of a helicopter tiedown test program. The primary purpose of this test was to evaluate a roller gear transmission in an aircraft installation and to conduct a 50-hour tiedown test at a power spectrum equivalent to helicopter military usage.

The roller gear transmission transmits 3,000 hp at 203 rpm to a helicopter main rotor head. The transmission is powered by two

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General Electric axial-flow turboshaft engines, each producing 1,870 hp at 18,966 rpm. A 19.85:1 roller gear unit is the final reduction stage in the transmission.

The 50-hour tiedown test program was successfully completed. Teardown inspection, however, revealed fatigue cracks in the electron-beam welds used in the fabrication of the roller gear components. Further testing of these cracked components was conducted in a ground test facility during which fracture of a roller gear pinion occurred. This report covers the event up to the fracture of this pinion.

In addition to the testing of the roller gear transmission, performance evaluations were made of the General Electric YT58-GF-16 engines, grease-lubricated tail and intermediate gearboxes used to transmit power to the tail rotor, the rotor head control system, and the general safety and adequacy of the test aircraft.

The tests performed showed that the roller gear transmission is a feasible high-reduction-gearing concept and that the aircraft controls and airframe modifications necessary to adapt the transmission into a integral helicopter subsystem are structurally airworthy.

PREFACE

This report, the fifth of six volumes dealing with the development of a 3,000-hp roller gear development program, covers the helicopter tiedown test of the roller gear transmission. The task was performed under Contract DAAJ02-69-C-0042, Task 1G162207AA7201, for the Eustis Directorate, U. S. Army Air Mobility Research and Development Laboratory, Fort Eustis, Virginia. This work is part of the overall effort to evaluate the roller gear concept when applied to helicopter transmissions.

The work was under the technical direction of Mr. James Gomez of the Eustis Directorate. Principal participants at Sikorsky included Mr. Lester Burroughs, Program Manager; David Adams, Cognizant Test Engineer; Lawrence Russell, Lizabeth Moriarty, Hugh Kearney and Patrick Laffey, Test Engineering; G. F. Gardner and Thomas Lally, Transmission Design; and pilots Stuart Craig, Charles Reine, Byron Graham, and Kurt Cannon.

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INTRODUCTION

The roller gear drive is a combination of the roller transmission, which transmits power through friction in a planetary arrangement of preloaded rollers, and a conventional geared planetary or epicyclic gear train in a compound arrangement. The rollers, which are integral with and located on either side of the gear members, have outside diameters coincident with the gear pitch diameters. In addition to providing support (in place of bearings) for the gear members, they also contribute to the driving power as in the pure roller drive. As a component portion of a helicopter main transmission, the roller gear drive is used in an epicyclic gear reduction in a star system arrangement, and has a ratio of 19.85 to 1.

As part of a long-range investigation of advanced helicopter drive train concepts, the U. S. Army funded a test of a model roller gear drive[1] and a parametric study of the roller gear system.[2] This work, plus later studies[3,4] indicated that the roller gear had good potential for reducing weight and improving the efficiency and reliability of helicopter transmissions. An early full-scale demonstration of the roller gear was a 75-hour test program of a transmission using an 1,100-hp roller gear drive.[5] Although limited in scope, the program did demonstrate that the roller gear transmission represented, with minor redesign, "an improvement in the state of the art for helicopter transmissions". Based on this work, a program to develop a full-scale helicopter roller gear transmission was initiated.

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1. ENDURANCE TEST OF AN-1 ROLLER GEAR DRIVE, USAAVLABS Technical Report 65-31, USAAML, Fort Eustis, Virginia, August 1965.

2. Dr. A. L.. Nasvytis and J. E. Bauer, PARAMETRIC STUDY ON THE ROLLER GEAR REDUCTION DRIVE, USAAVLABS Technical Report 64-29, USAAML, Fort Eustis, Virginia, June 1965.

3. C. W. Bowen, C. E. Braddock, and R. D. Walker, INSTALLATION OF A HIGH-REDUCTION-RATIO TRANSMISSION IN THE UH-1 HELICOPTER, USAAVLABS Technical Report 68-57, USAAML, Fort Eustis, Virginia, May 1969.

4. L. R. Burroughs and N. L. Chivaroli, CH-54A HIGH SPEED ROLLER GEAR TRANSMISSION FEASIBILITY STUDY, Sikorsky Engineering Report SER-64202, January 1970.

5. A. L. Nasvytis and J. H. Hemlein, 1100-HP ROLLER GEAR DRIVE, USAAVLABS Technical Report 70-3, USAAML, Fort Eustis, Virginia, January 1970.

Sikorsky Aircraft, under contract with the Eustis Directorate of the U. S. Army Air Mobility Research and Development Laboratory, is conducting a program involving the design, fabrication, and testing of a roller gear transmission for use with the Sikorsky Aircraft S-61 helicopter. The design, fabrication, and 200-hour bench test parts of the program have been successfully completed. This report covers the aircraft ground test portion of the program.

The bench test program[6] included a no-load lubrication test, a gear pattern development test, initial development tests, a 200-hour endurance test and an efficiency test. The tests were successfully completed after some design modifications to the roller gear unit components. The changes, resulting from fractures originating at electron-beam-welded joints, were incorporated during initial development tests which preceded the 200-hour endurance tests. The tests showed that the efficiency of the roller gear transmission is comparable to that of transmissions of conventional design.

For the ground test, a bailed S-61 type NSH-3A aircraft, shown in Figure 1, was modified to accept the roller gear main transmission. In addition, the aircraft was equipped with YT58-GE-16 turboshaft engines, a modified rotor control system, and tail-rotor-driven grease-lubricated tail and intermediate gearboxes. The ground tests included control system proof tests and a 50-hour tiedown test which included evaluations of transmissions, controls, engine, and airframe.

TRANSMISSION DESIGN

The design requirement for the roller gear transmission, as outlined in Table 1, are for a 27,000-pound gross weight growth version of the S-61 type helicopter.

The roller gear transmission is designed to transmit the full power capability of two YT58-GE-16 engines (3,740 hp dual engines, 1,870 hp single engine). The gearbox consists of three reduction stages: bevel, combining spur, and the roller gear drive. The aircraft accessory drive pads, located in the aft portion of the gearbox, and the tail rotor are driven by a bevel gear located on the combining spur gear shaft.

6. G. F. Gardner and R. E. Haven, LABORATORY BENCH TEST, 3,000-HP ROLLER GEAR TRANSMISSION DEVELOPMENT PROGRAM, USAAMRDL Report 73-98D, USAAMRDL, Fort Eustis, Virginia, May 1974.

Figure 1. Helicopter, S-61 Type NSH-3A

TABLE 1. S-61 ROLLER GEAR TRANSMISSION DESIGN REQUIREMENTS		
Location	Speed (rpm)	Power (hp max)
Input Drives		
Dual engine	18,966	3,700
Single engine	18,966	1,870
Main Rotor, Roller Gear Stage		
Output	203	3,000
Tail Takeoff Total	7,031	700
Tail Rotor Takeoff	3,025	565
Accessory Drives		
Generator (Left)	8,100	54
Generator (Right)	8,100	54
Tachometer	3,900	1
Servo Hydraulic Pump	4,107	6.5
Aux Servo Hydraulic Pump	4,005	6.5
Utility Hdraulic Pump	4,055	13
Lubrication Pump	5,149	4

The actual arrangement of these components is shown in the gearbox cross-sectional drawing, Figure 2. The engine output shaft drives the input pinion of the first-stage spiral bevel gear mesh at 18,966 rpm. The centerline of the spiral bevel gear of this 3.05-to-1 first-stage reduction is parallel to the centerline of the main rotor shaft. Within the bevel gear shaft is an overrunning cam-roller type freewheel unit. The output of the freewheel unit drives the pinion of the second-stage 1.54-to-1 spur gear reduction set, which combines the power of the two inputs onto a centerline common with the main rotor shaft.

The last stage, Figure 3, is the roller gear drive unit with a reduction ratio of 19.85 to 1. The unit consists of a fixed cage with two stationary rows of pinions, ring gear output, and sun gear input. A split power path at the sun gear and ring gear induces symmetrical loading for each mesh in the roller gear unit. Two rollers per mesh, whose diameters equal the gears' pitch diameters, straddle the gears of the sun, first-row pinions, and second-row gears. The seven first-row pinions are positioned by the sun and second-row rollers and are thus accurately located by three contact points. Seven second-row gears are similarly positioned by the rollers of the

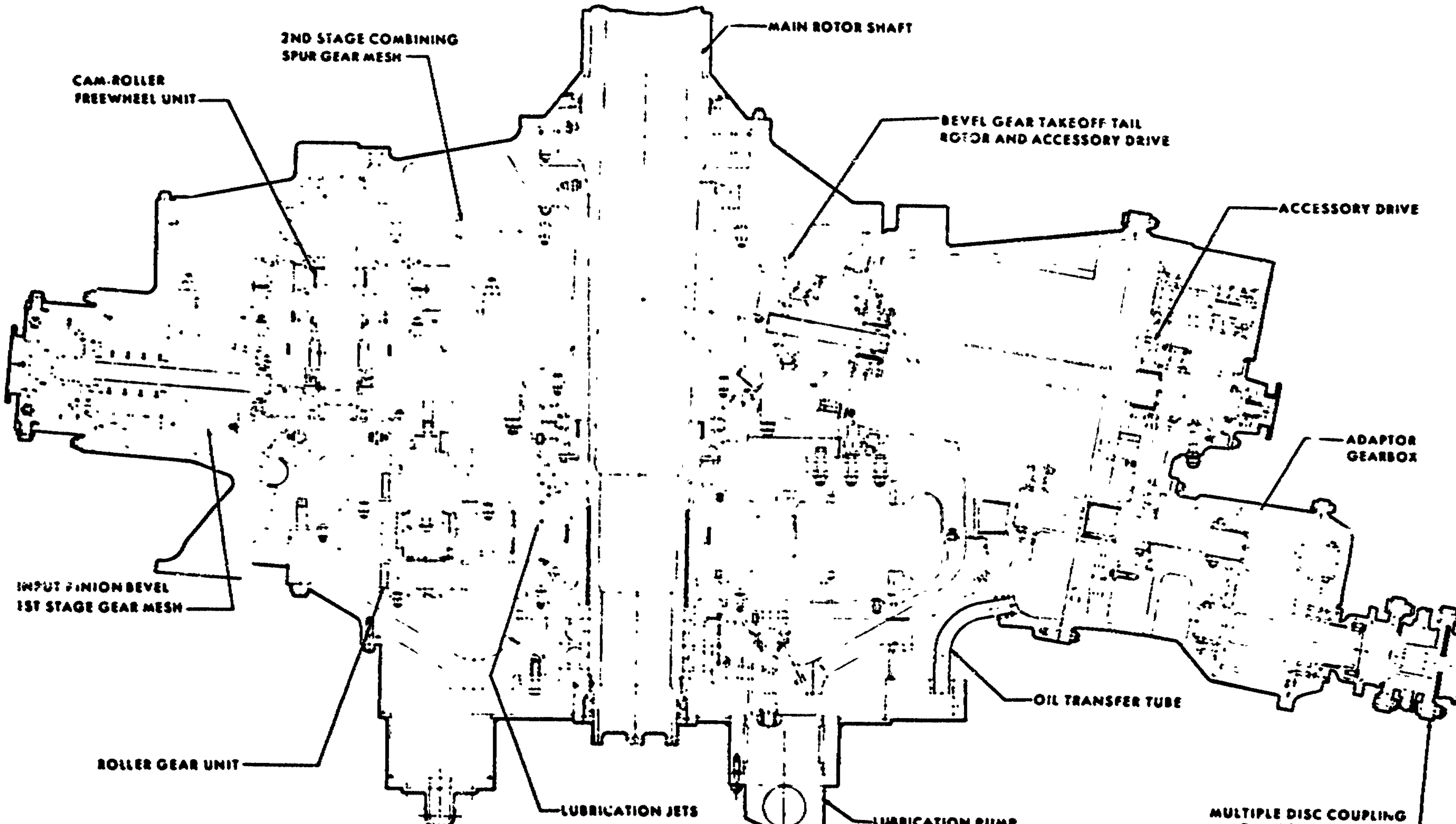

Figure 2. Cross-Sectional Drawing, Roller Gear Transmission

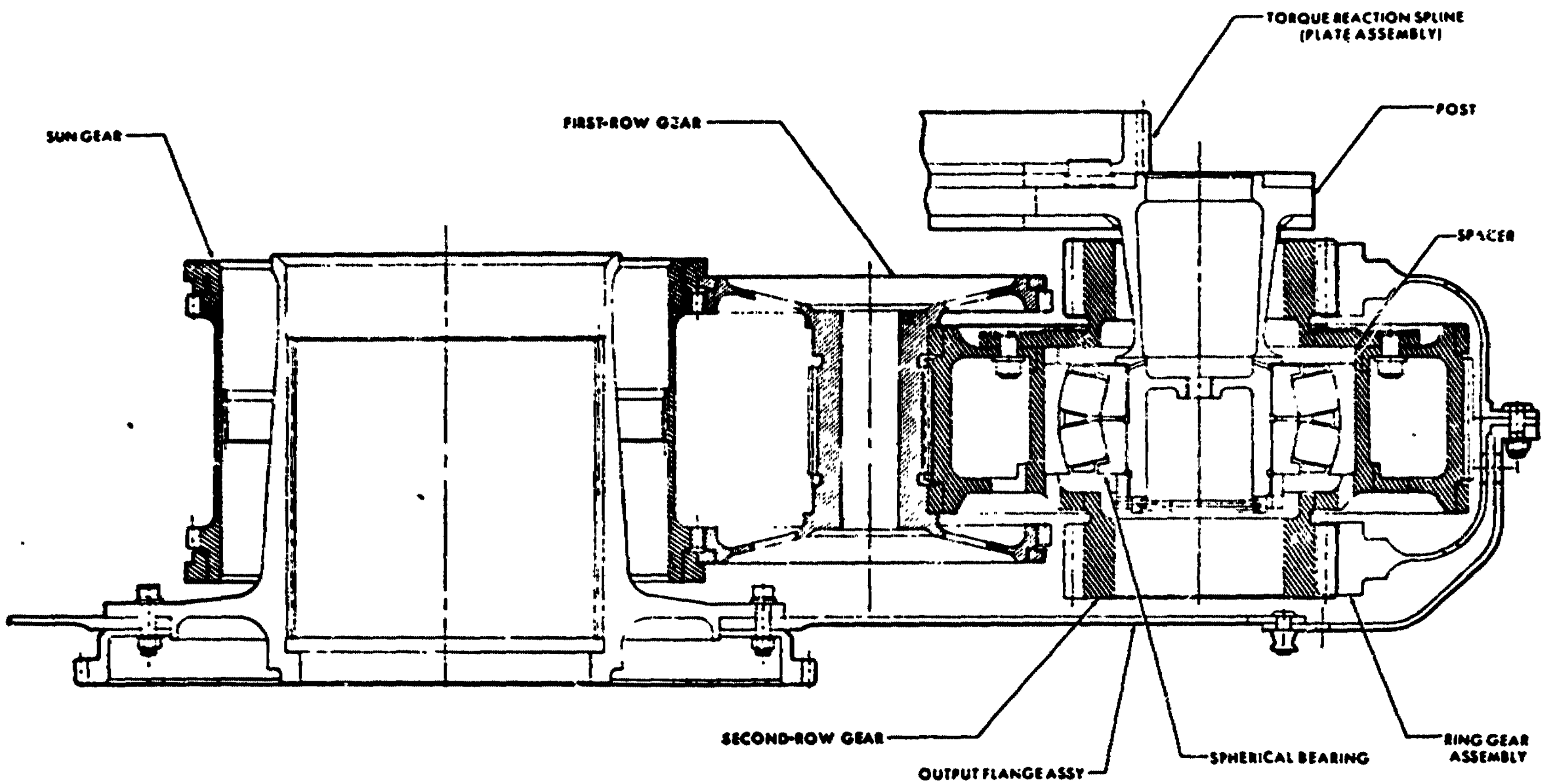

Figure 3. Drawing, Roller Gear Drive

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first-row pinions and the separating component of the ring gear. This gear separating force ensures contact of the rollers at all times. The symmetry of the design of the rollers and the forces induced on them allows the planets to be held parallel. Flanges on the rollers provide axial location of the first- and second-row pinions. Torque is reacted on the roller gear drive unit through spherical bearings located in the second-row gears. Power is thus transmitted by the gear teeth while kinematic stability is provided by the rollers.

This design eliminates planet bearings except in the last row, where they are necessary to transmit the reaction torque, and ensures parallel alignment of all elements within manufacturing tolerance. The roller gear drive unit has inherently more stable load-sharing characteristics than conventional planetaries due to the accurate positioning of the pinions by the rollers. Figure 4 shows the arrangement of the roller and gear members of the drive. Figure 5 is the assembled unit.

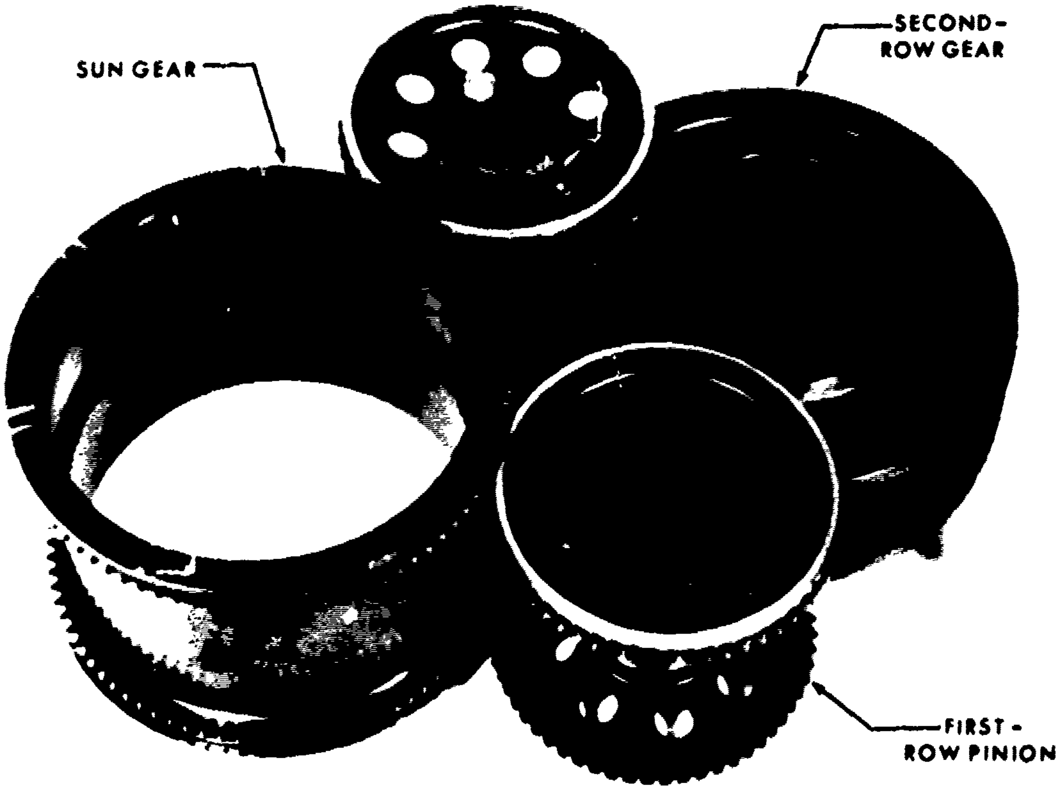

Figure 4. Component Arrangement, Roller Gear Unit

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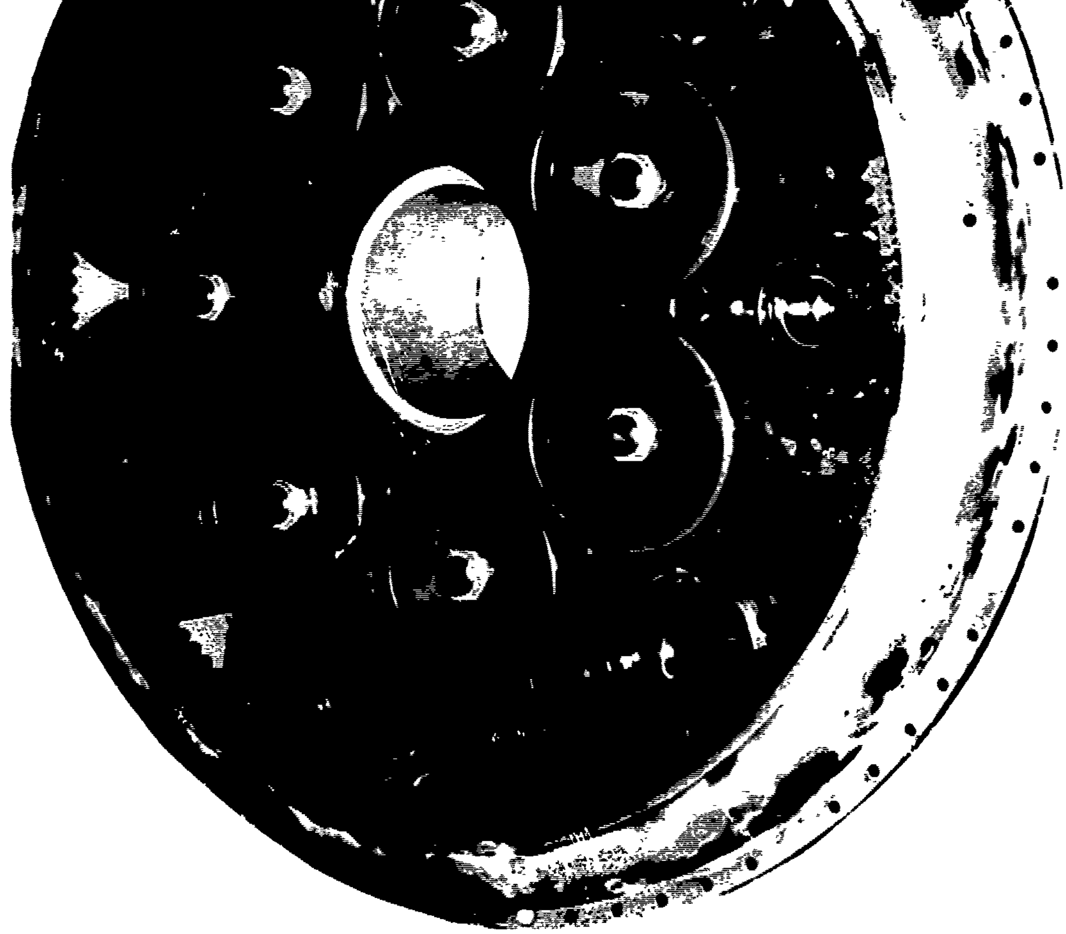

Figure 5. Assembled Unit, Roller Gear Drive

The roller gear transmission was designed using current state-of-the-art design practice, materials, and stress levels. Bearings were designed for 3000 hours B-10 life. All major bearings were made from 52100 CVM steel. All primary power gearing was made from AMS 6265 (AISI 9310 CVM) case carburizing steel. Gearbox shafting is 9310 or 4340 steel.

The smaller gearbox housings are AZ-91C magnesium casting, while the main housing, shown in Figure 6, is made from ZE41A, a zirconium base magnesium alloy. This casting material was chosen because of its excellent strength and moldability.

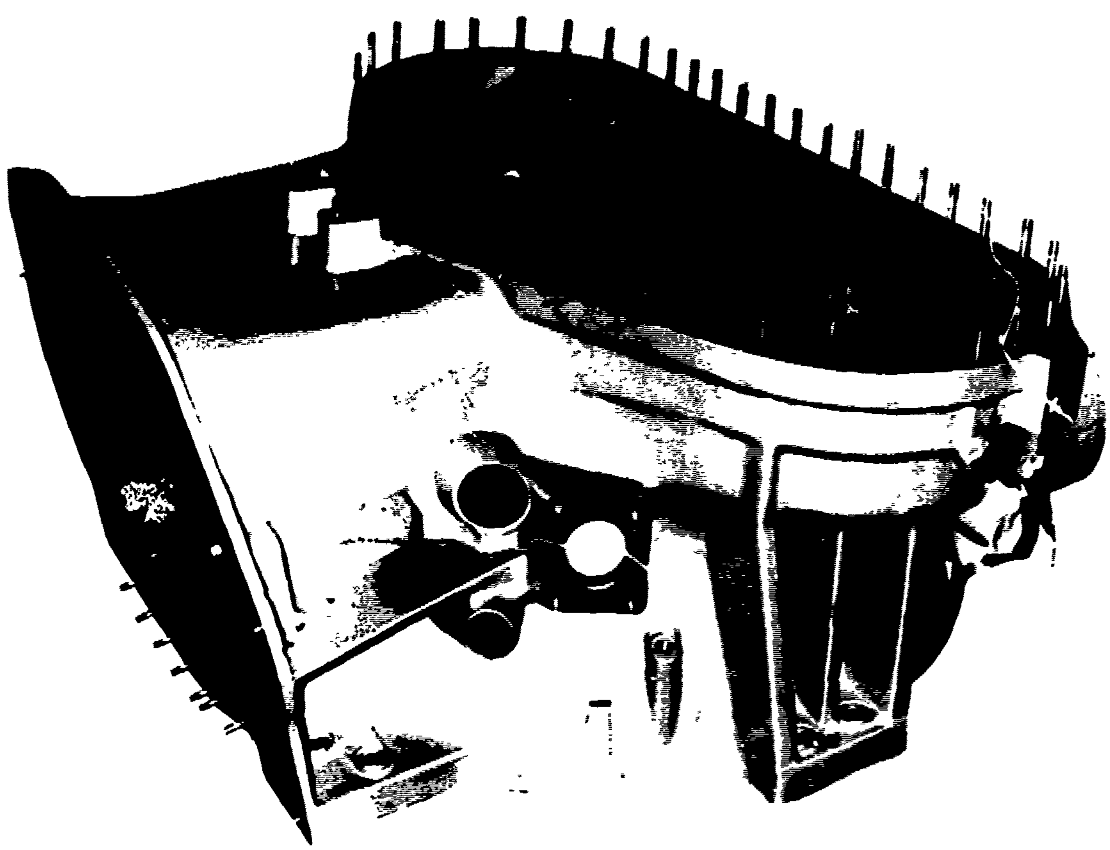

Figure 6. Main Housing, Roller Gear Transmission

The roller gear hardware presented unique manufacturing problems. For this advanced development unit, extremely close tolerances were demanded. The timing between gear members in the "stepped" roller gears of the first- and second-row pinions was held extremely close, as was the concentricity of the rollers to one another and to the pitch diameter of each gear. Gear members of roller gear pinions were joined by electron-beam-welding techniques, as were the rollers to the pinion assemblies. The drive sides of the two end gears of the first- and second-row pinions were "timed" to the center gear to within ± 0.0002 inch. Figure 7 depicts the first-row pinion timing. The rollers were held concentric with one another and the gear pitch diameters to within 0.005 inch total indicated reading (T.I.R.). The second-row gears were made to similar tolerances. Both first- and second-row pinions were manufactured in matched sets of seven pinions.

The roller gear ring gear presented a special design problem. To provide the necessary flexibility for equal load sharing on this split ring gear, a thin web was required on this 27.6-inch pitch-diameter gear. To produce this flexibility and maintain tight tolerances on the finished part, the gear teeth were hobbed, carburized, heat treated, and finish ground, and then the gear web was machined to a final thickness of 0.090 inch.

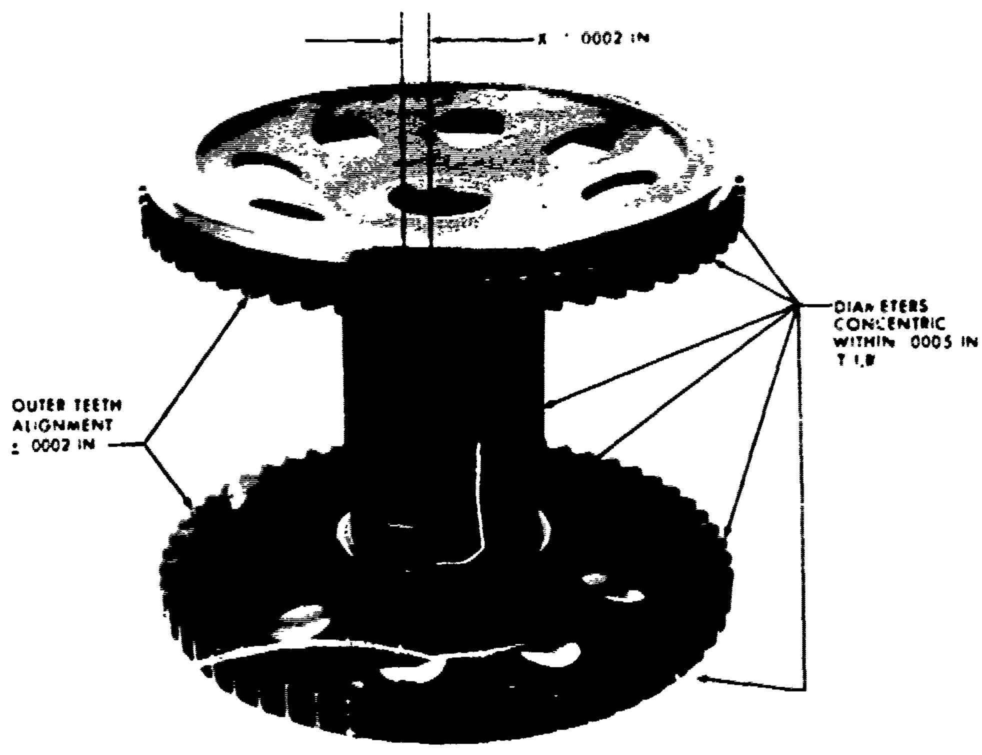

Figure 7. Gear Timing, First-Row Pinion

TRANSMISSION BENCH TEST, 200-HOUR ENDURANCE

The objective of the bench test program, which included no-load lubrication tests, gear pattern development tests and endurance testing, was to demonstrate that the transmission system components met the design requirements. The program was designed to develop and debug the transmission systems, to determine the mode of failure of the system component, to demonstrate that all catastrophic modes are out of the planned operating range, and to demonstrate that all noncatastrophic modes of failure are detectable.

The roller gear transmission tests were conducted in the S-61 regenerative bench test stand, Figure 8, which tests two gearboxes installed "back-to-back" at the same time. The test gearbox is loaded in the same manner as in the aircraft installation. Although rotation of the dummy (or slave) gearbox components is in the opposite direction, all torques are in the same direction as the test box and all gears are loaded on the correct side of the gear teeth. All components other than those used in the lubrication system are essentially the same as those in the test gearbox.

The first test performed on the roller gear transmission was the no-load lubrication test, the primary objective of which was the determination of optimum lubrication parameters. The factors under evaluation were the amount of lubricant and jet sizes required to provide adequate transfer of heat from the dynamic components of the gearbox while minimizing frictional losses caused by oil churning. The test also locates any lubricant flow problems such as restrictive oil paths and improper drainage. Ancillary objectives included checks on the mechanical functioning of the roller drive gearbox and test instrumentation.

The primary objective of the gear pattern development test was the evaluation of gear patterns generated within the gearbox when operated under load. Examination of the gear patterns provided verification of the manufacture of the gears and the proper loading and alignment of gears and bearings.

Initial development testing included evaluation of the manufacturing methods used in the fabrication of the sun gear and first- and second-row pinions of the roller gear drive. These gears were manufactured with the use of electron beam welds. Electron beam welding is a relatively recent development which employs a highly concentrated beam of electrons to melt and thereby fuse components together. Since this program marked the first time that electron-beam-welded gears have been used extensively in a helicopter main transmission, the initial development testing was necessary to check the endurance capabilities of these gears before the start of the 200-hour

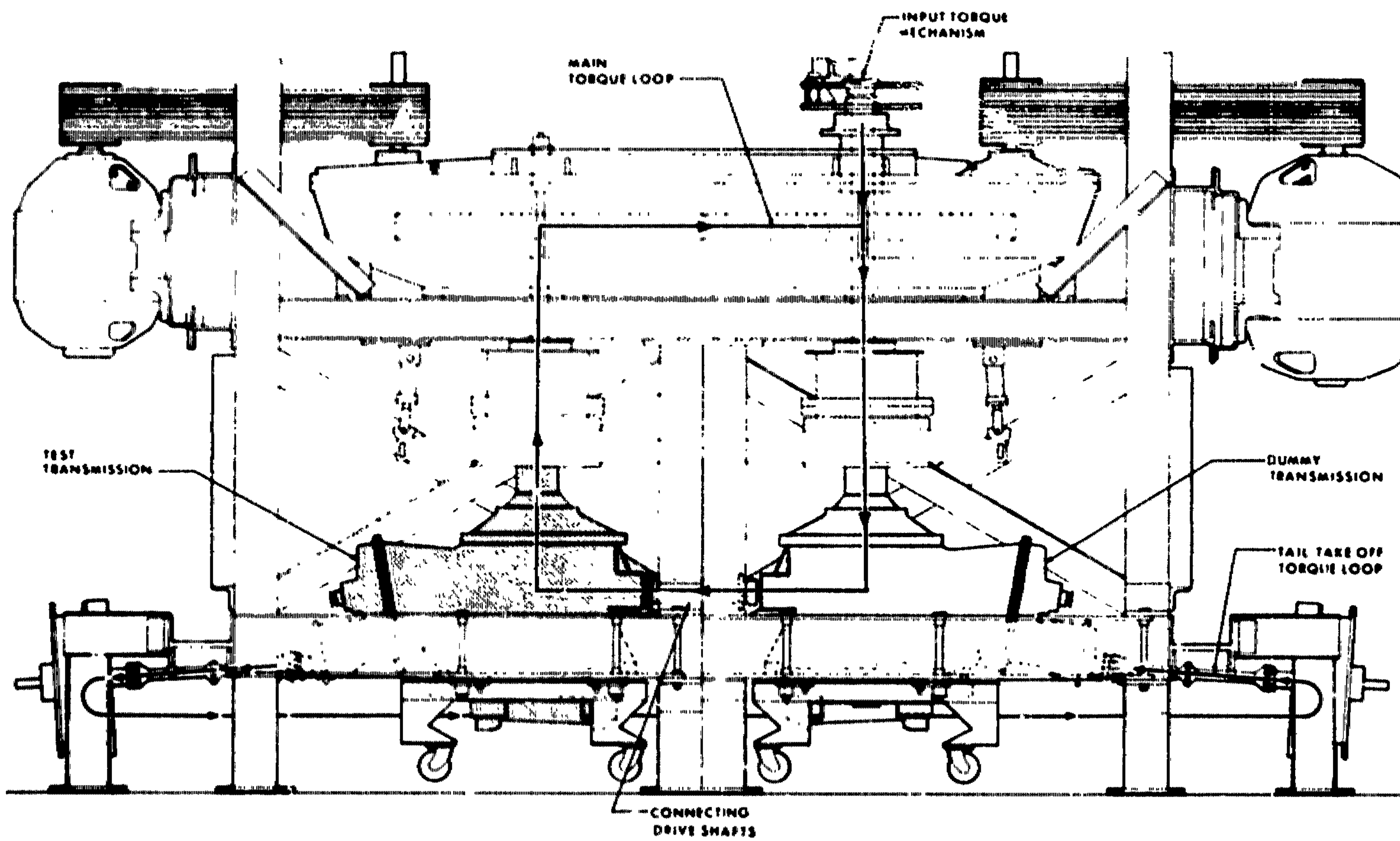

Figure 8. Regenerative Bench Test Facility

endurance test. Modifications necessary to ensure failure-free performance of the electron-beam-welded gears for extended periods of time were made as a result of this phase of testing.

The 200-hour endurance test was designed to evaluate the effects on the roller gear transmission of long-term operation in a fatigue environment. The test was divided into two parts. After 110 hours were completed per the test spectrum of Table 2, both test and dummy gearboxes were removed from the test stand for inspection. Upon completion of inspection, the gearboxes were replaced in the test stand, and the test continued for an additional 90 hours per Table 3.

TABLE 2. ENDURANCE TEST SPECTRUM - 110 HOURS

Time (hr:min)	Total Input Power (hp)	Tail Power (hp)
15:00	1,100	250
50:00	1,950	250
25:00	2,400	250
10:00	2,700	250
6:30	3,000	425
1:30	1,950	425
1:30	3,560	425
:30	3,700	425

TABLE 3. ENDURANCE TEST SPECTRUM - 90 HOURS

Time (hr:min)	Total Input Power (hp)	Tail Power (hp)
0:45	400	40
7:30	1,100	250
32:00	1,950	250
12:30	2,400	250
7:00	2,700	250
19:30	3,000	425
4:30	1,950	425
4:30	3,560	425
1:45	3,700	425

Following completion of the testing, both gearboxes were removed from the test stand and completely disassembled. All gearbox components were subjected to magnaglow inspection. Those components containing electron beam welds were also subjected to pulse-echo ultrasonic inspection to check the integrity of the welds. Coincident with the 200-hour endurance test, an efficiency test was conducted, the objective of which was the accurate determination of the efficiency of the roller gear drive transmission by means of heat loss calculation. This was accomplished by insulating the test gearbox with a sheet of fiberglass insulation on all nonrotating surfaces. The lube oil was plumbed through a water-oil heat exchanger with both oil lines and heat exchanger insulated. During the test, input power, tail takeoff power, main shaft power, water-in temperature, water-out temperature, and water mass flow rate were continuously recorded. From the data gathered, the heat loss (a measure of the inefficiency of the system) was calculated from the mass flow rate and the enthalpy of the heat exchanger water.

Results, 200-Hour Bench Test

The no-load lubrication and gear pattern development tests were completed with good results. The roller gear unit exhibited excellent load-sharing characteristics with very uniform loading of both first- and second-row pinions.

Initial development testing produced cracking in the first- and second-row pinion gears originating from electron beam welds. These problems were resolved by redesign of the affected parts. Ultrasonic inspection methods and acceptance criteria for electron beam welds were developed during this program and proved to be excellent tools in the evaluation of these components.

The 200-hour endurance test was successfully completed without major problems. The condition of the gears and roller surfaces at the end of testing was excellent.

The efficiency of the roller gear transmission compared favorably to the efficiencies of transmissions of conventional design. The frictional loss of the gearbox was found to be 100 hp with 3,740 input hp, an efficiency of 97.3%.

As a result of more than 250 hours of testing, it was concluded that the roller gear drive was a feasible reduction unit for helicopter transmissions and that the program should continue into the tiedown test program.

TIEDOWN TEST HELICOPTER

The ground test vehicle for the roller gear tiedown program was a Navy model NSH-3A helicopter. This S-61 type series helicopter was developed as a twin turbine-powered growth version of the S-58 single reciprocating-engine helicopter. It was designed for extended antisubmarine warfare missions and equipped for carrier operation. The basic NSH-3A helicopter has a gross weight of 19,100 pounds and is powered by two General Electric T58-GE-8B engines, each developing 1,250 hp at 30 minutes rating.

The roller gear drive transmission was designed specifically around the requirements of the General Electric YT58-GE-16 engine and for installation in an S-61 type helicopter. Figure 9 shows the aircraft general arrangement. A summary description of the test aircraft is given in Table 4.

TABLE 4. TEST AIRCRAFT DESCRIPTION

Helicopter Type:	NSH-3A
Aircraft Bureau Number:	152105
Engine Manufacturer:	General Electric
Engine Type (2):	YT58-GE-16
30-Minute Rating	1,870 hp
Maximum Continuous Rating	1,700 hp
Number of Main Rotor Blades:	5
Main Rotor Speed:	203 rpm
Blade Type:	Constant chord NACA 0012
Rotor Radius:	31 ft
Blade Twist:	8°
Blade Chord:	18.25 in.
Number of Tail Rotor Blades:	5
Tail Rotor Speed:	1,243 rpm
Blade Type:	Constant chord NACA 0012
Blade Chord:	7.34 in.
Tail Rotor Diameter:	10 ft 4 in.
Maximum Gross Weight:	19,100 lb

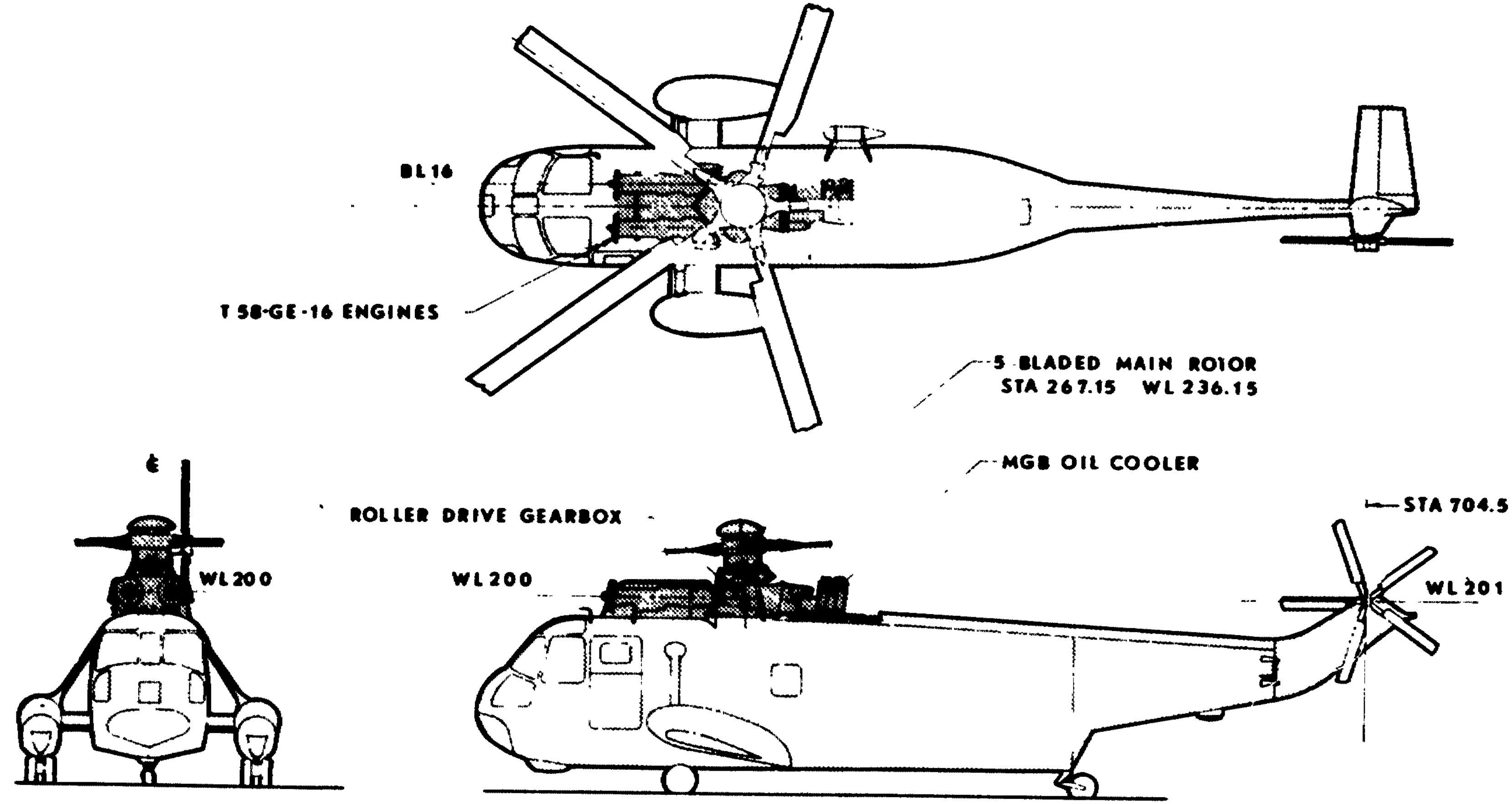

Figure 9. Aircraft General Arrangement

ENGINE SYSTEM

The YT58-GE-16 engine is a 1,870-shp axial-flow compressor turboshaft engine incorporating a two-stage free turbine, mechanically independent of the gas generator rotor. Within its normal operating range, power turbine speed can be maintained or regulated independent of output power. The YT58-GE-16 gas generator utilizes the existing T58-GE-10 ten-stage compressor and annular combustor with a new two-stage air-cooled gas generator turbine. Stall-free operation is provided by use of the variable stator principle in the compressor. The inlet guide vanes and stator vanes in stages one, two, and three are variable.

The general arrangement of the engine installation on the roller gear aircraft is shown in the drawing of Figure 10. Various views of the installation are shown in Figure 11. In the center picture can be seen accelerometers attached to the static torque tube and gimbal yoke; these are used for instrumentation during engine vibration tests.

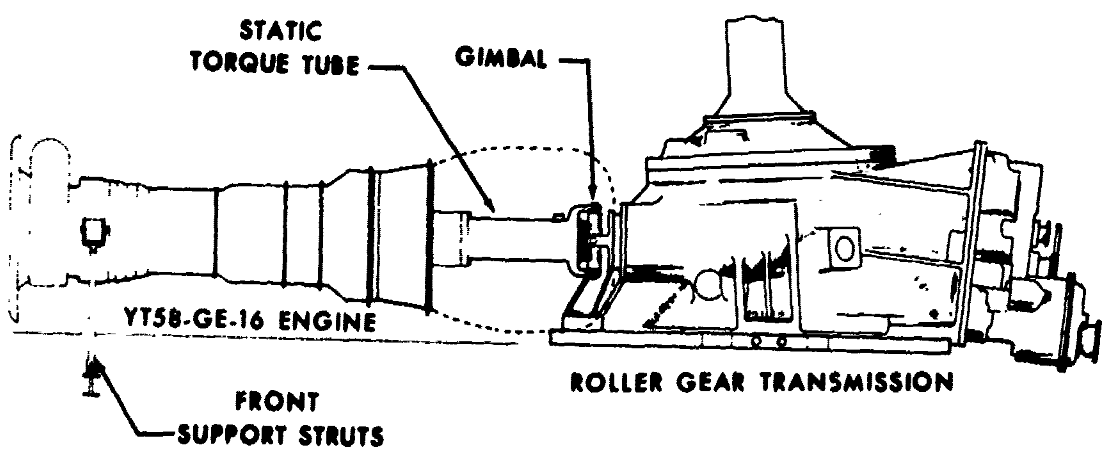

Figure 10. Engine Installation Drawing

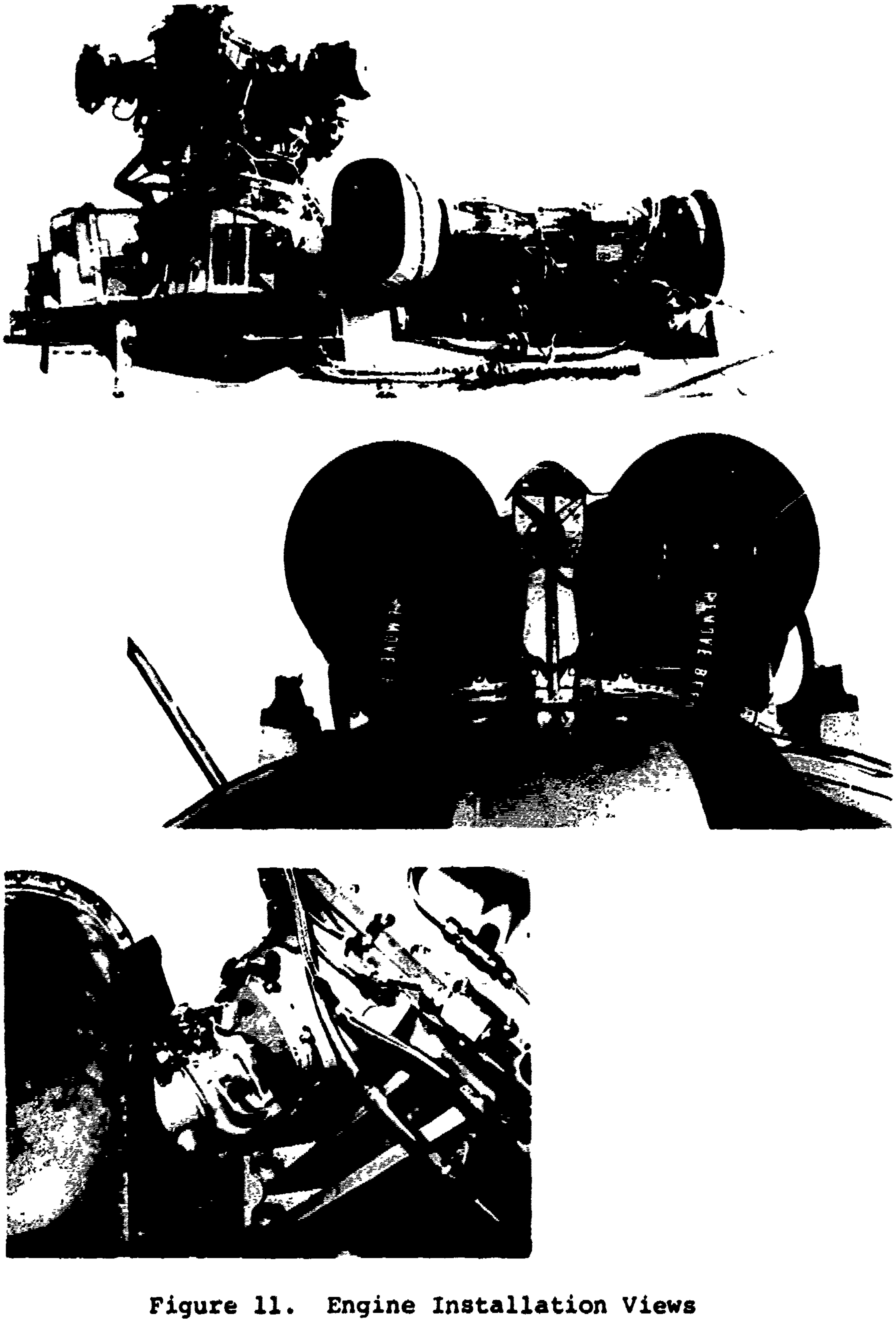

Figure 11. Engine Installation Views

The engines are mounted on a three-point suspension system consisting of an aft gimbal and two elastomeric front supports that are free to flex. These front supports are attached through vertical struts to the engine support ring at station 156.378. Each engine is supported at the rear by bolting a gearbox static torque tube to the engine power takeoff pad. This is attached to the gearbox input pad through elastomeric mounts in a gimbal which allows two-axis motion for alignment of the engine to the gearbox. The pivot point of this gimbal is coincident with that of the main flex gear coupling of the high-speed input drive shaft.

Between the engine and gearbox input is a phase-line torquemeter mounted on the engine drive shaft (Figure 12). The torque-metering system was designed in accordance with the specifications of Reference 7. Attached to each end of the drive shaft are outer shafts on which are machined, on the free end, equally spaced pole pieces. Under the influence of torque, the drive shaft twists, causing a displacement of the pole pieces. A magnetic pickup located on the stationary torque tube converts the relative position of the pole pieces into a series of electronic pulses which are operated upon to produce a voltage proportioned to the applied torque. This voltage is read out on a torque indicator.

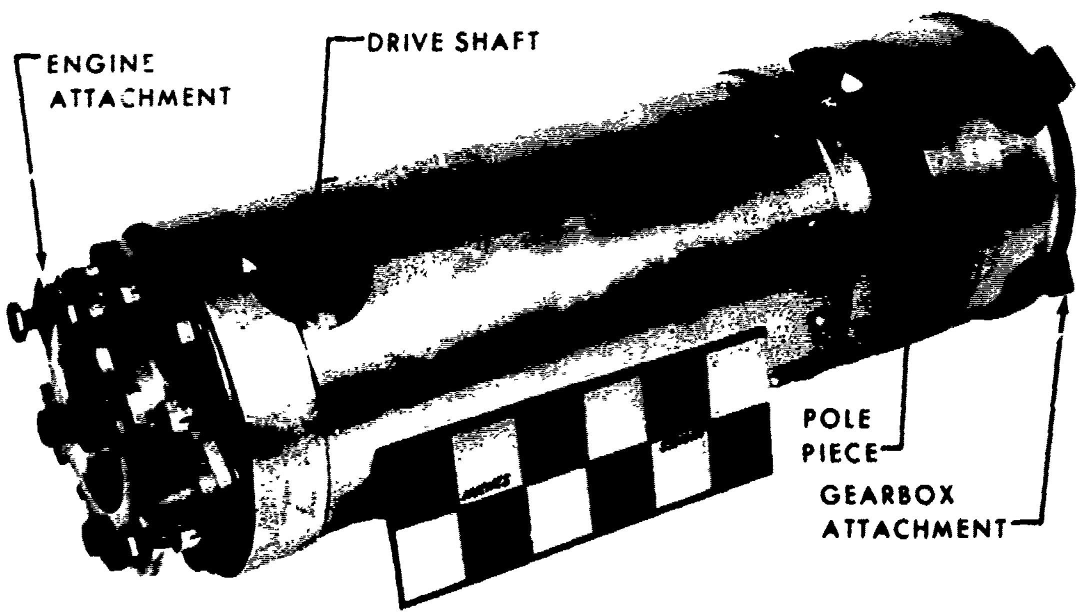

Figure 12. Engine Drive Shaft

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7. SPECIFICATION FOR DUAL ENGINE TORQUE MONITORING SYSTEM, Sikorsky Engineering Report MC-EGD-3, Sikorsky Aircraft, Stratford, Connecticut, December 1969.

TRANSMISSION SYSTEM

The roller gear transmission is located on a 2-inch-thick adaptor plate. Twelve mounting bolts of the roller gear transmission are screwed into the plate, which is in itself bolted to the NSH-3A airframe by six bolts.

Located on the rear cover of the main transmission are power takeoff pads for fitting two generators, a tachometer, three hydraulic pumps, the rotor brake, and one lubrication pump as shown in Figure 13.

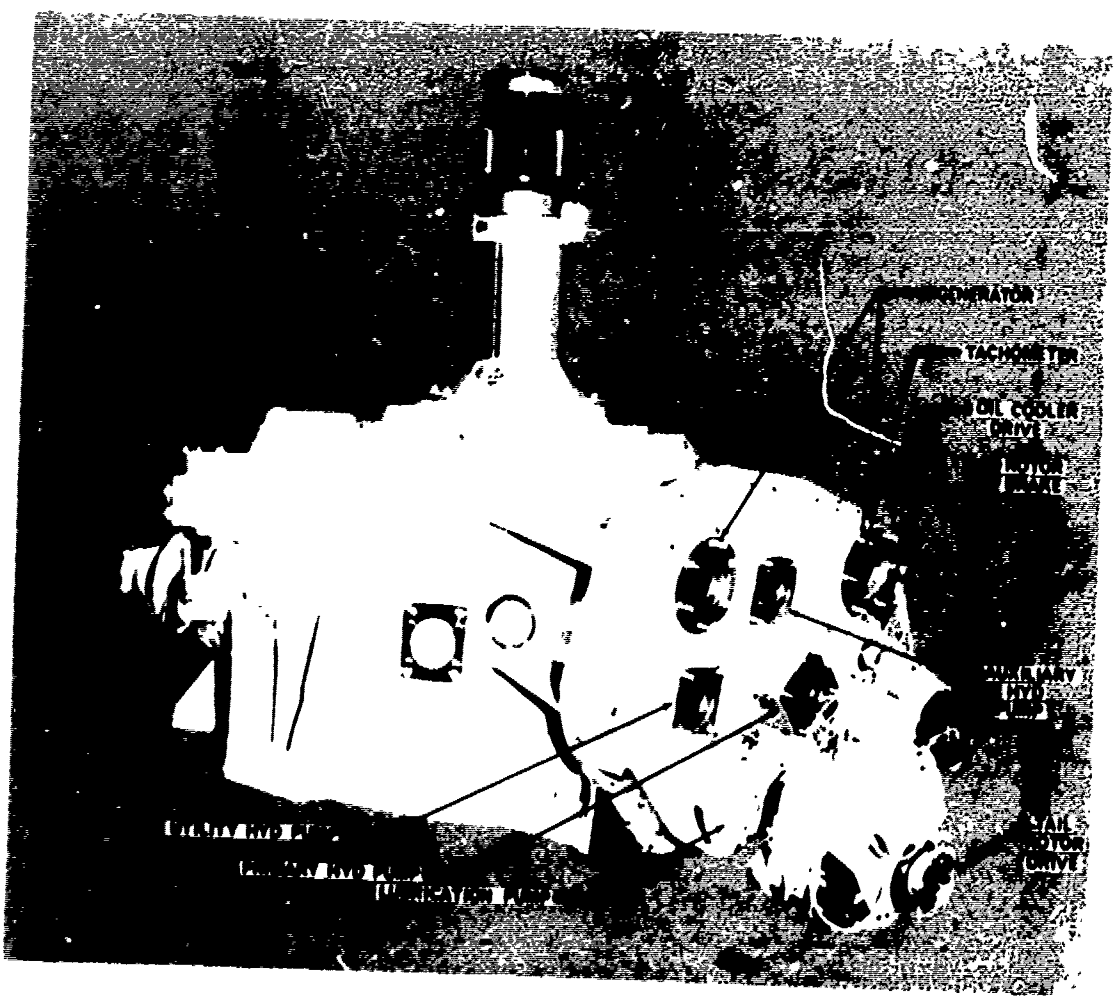

Figure 13. Accessory Section, Roller Gear Transmission

Two gearbox-driven lubrication pumps, one mounted on the accessory section and the other on the lower sump, are each capable of supplying the required amount of oil for adequate lubrication of the main transmission. This oil is collected from the sump via the two pumps and fed by a common line into a 46 micro-inch cleanable element filter. Oil then passes to an oil cooler through which air is blown from a fan driven from the rear cover of the main transmission. This clean, cooled oil is then fed back into the main transmission.

To adapt the roller gear transmission to the existing NSH-3A tail drive system, an adaptor gearbox was used. A multiple disc coupling assembly attached to the tail drive flange and shown in Figure 14 absorbs the angular misaligmont of the tail drive shafting and adaptor gearbox output.

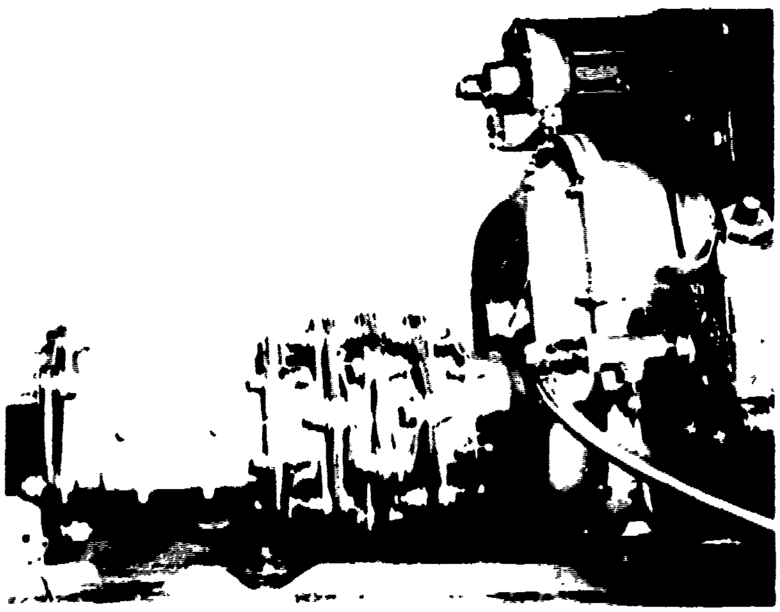

Figure 14. Multiple Disc Coupling, Tail Drive Shaft

The tail and pylon drive shafts shown in Figure 15 transmit power from the main transmission to the tail rotor. The tail shafting (between the main transmission and intermediate gearbox) is supported on the fuselage by five viscous damped bearings. The intermediate gearbox incorporates two spiral bevel gears which transmit power to the tail gearbox without speed reduction. The tail gearbox uses a 2.44:1, 90-degree spiral bevel gear set to drive the tail rotor at 1,243 rpm. Both tail and intermediate gearboxes, depicted in Figure 16, are lubricated with Helicopter Transmission Grease conforming to MIL-G-83363 (USAF); this grease is packed around the gear meshes and bearings and retained by shields.

FLIGHT CONTROL SYSTEM

The S-61 type helicopter utilizes a single main rotor and a torque compensating tail rotor. The flight control system is composed of two (auxiliary and primary) separate hydraulic-powered positional servo systems, series connected with mechanical linkages.

Located within the cockpit are the azimuth (control stick), the collective pitch control lever, and directional control pedal. Through mechanical linkages, motions of the controls are transmitted to auxiliary servos which:

a. React rotor head loads in the event that a malfunction occurs in the primary servo system.

b. Provides a boost to overcome friction in the linkages to the primary servos.

c. Reacts rotor head loads continuously in the directional control channel.

The output from the auxiliary servo is directed to the mixing units, located aft of the cockpit, which combine all motions through mechanical linkages into proportional signals to the primary servos and, in the directional channel, to the tail rotor pitch control mechanism. Due to the configuration of the roller gear transmission main housing, the S-61 type 90-degree spacing of the primary servos (which are attached to the housing) is relocated to a 120-degree spacing as depicted in Figure 17.

The 120-degree spacing of the primary servos necessitated a coordinated differential motion on all three servos to establish the swashplate (cyclic) plane of inclination. An analog cyclic mixer (swashplate) is installed in the control closet above the AFCS servo as shown in the schematic layout, Figure 18. The mixer inputs, longitudinal and lateral, are aligned with the AFCS servo outputs. Three mixer outputs are geometrically aligned with the 120-degree spacing of the primary servo. A longitudinal input causes the swashplate to rotate about the lateral input axis and results in a cyclic plane of inclination required for control response. The three outputs are displaced proportional to the tilt of the mixer. The resultant output signals position the three primary servos and tilt the main rotor swashplate at the same angle of inclination as the analog mixer. Lateral input signals tilt the analog mixer about the longitudinal input axis with corresponding outputs to the primary servos. A scissor assembly prevents rotation of the analog mixer. The mixer accepts any combination of lateral and longitudinal input motions with corresponding output motions to the primary servos.

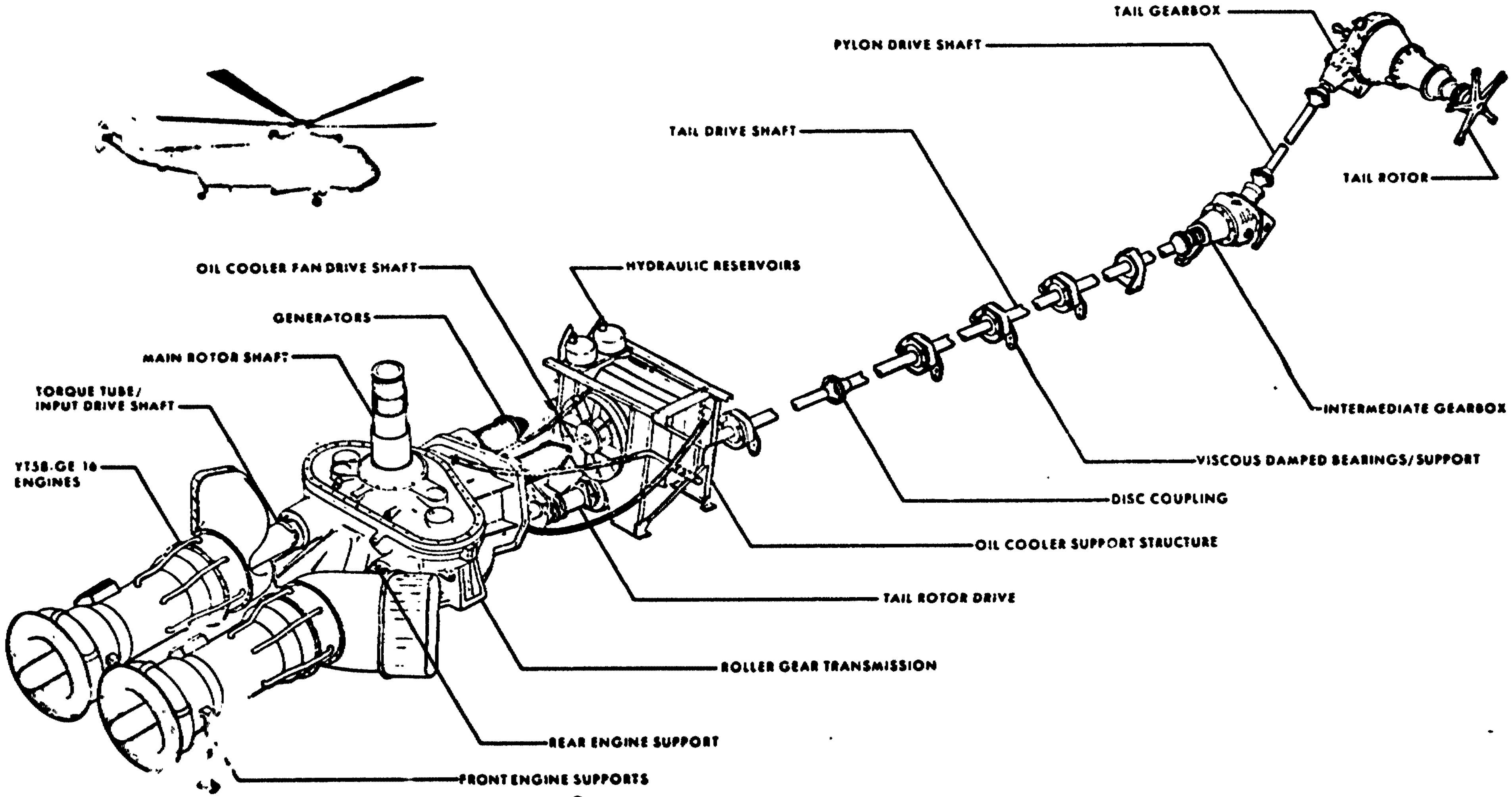

Figure 15. [illegible] Shaft Arrangement, Roller Gear Aircraft

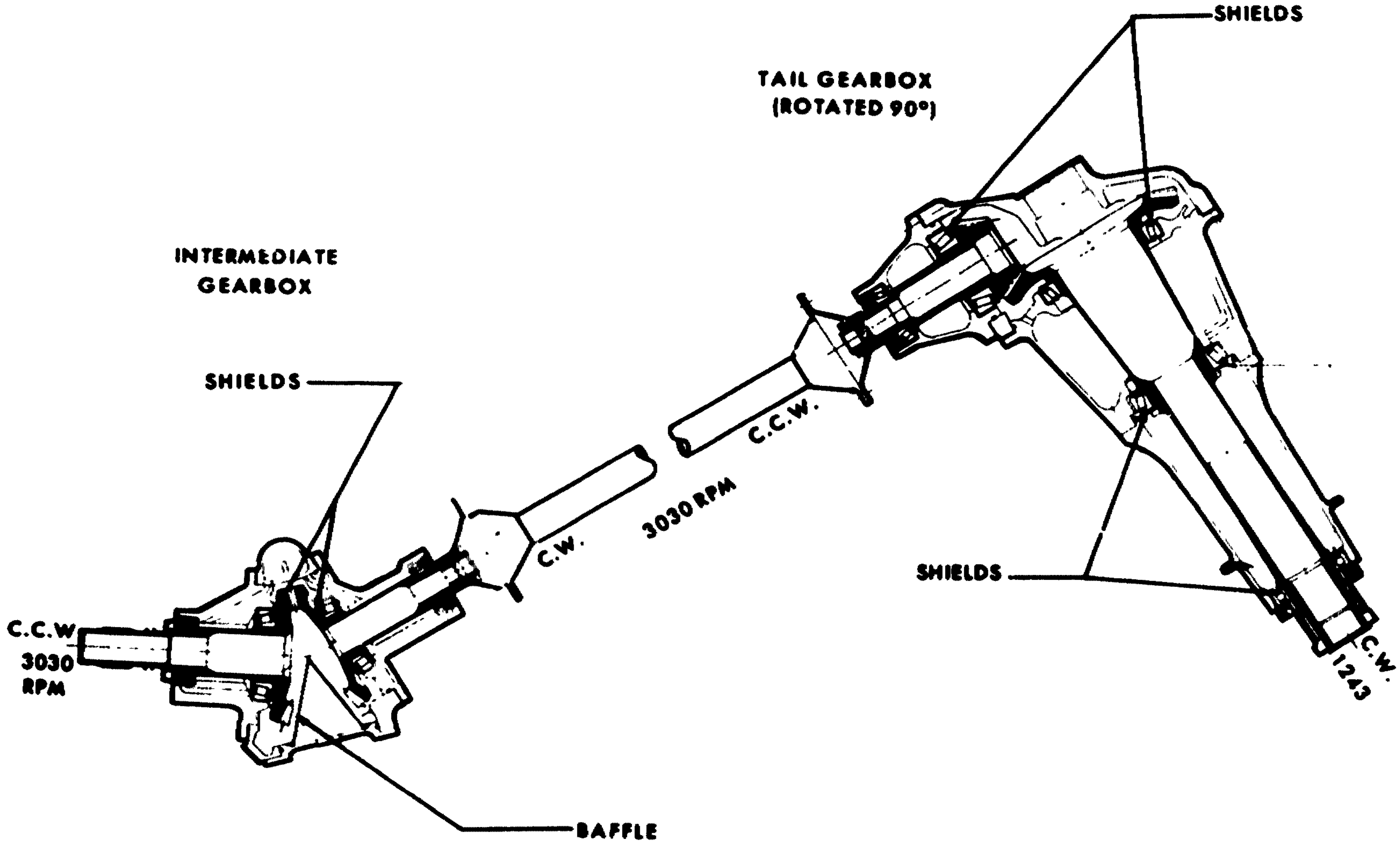

Figure 16. Tail and Intermediate Gearboxes, Grease Lubricated

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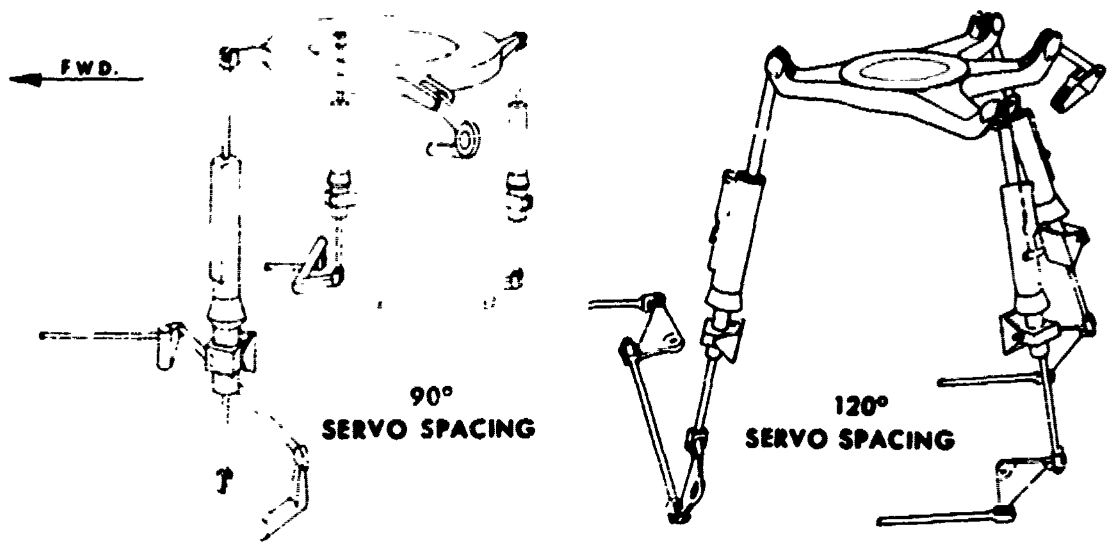

Figure 17. Primary Servo Spacing Schematic

The rotor head swashplate is composed of a stationary (non-rotating) star and a rotating star, which along with rotating pushrods are used to co. ert linear motion of the primary servos into angular rotation of the main rotor blades about their feathering axes. The position of the primary servos, as established by the cumulative pilot and AFCS inputs, determines the plane of the swashplate assembly. When the swashplate is other than perpendicular to the main rotor shaft, a sinusoidal cyclic pitch change is imparted to each blade as it traverses a complete revolution. This results in flapping angle variations experienced by the blades which establish the tip path plane and consequently the direction of the azimuth thrust vector; a change in the collective pitch is provided by the axial displacement of the swashplate along the main rotor shaft, which will cause a change in the coning angle and thus the magnitude of the resultant force vector. Rotational drag forces on the stationary star are reacted by a scissor link assembly w. imposes no restraint on the positioning of the swashplate. A separate scissor imparts the torque to turn the rotating star with the rotor head.

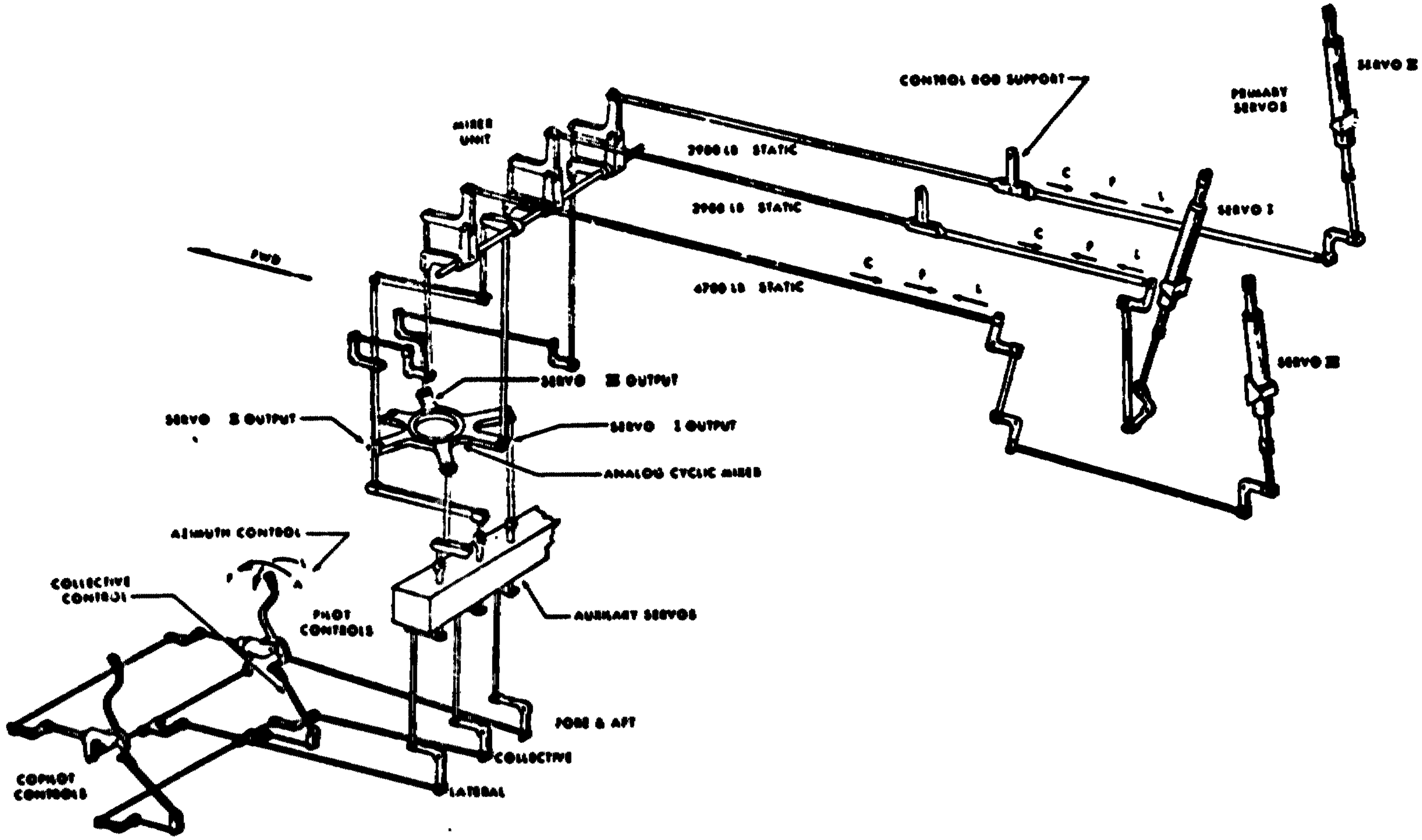

Figure 18. Control System Layout Schematic

Changes to the rotor head include the installation of additional pushrods to provide increased rotor collective range, thereby enabling the 3,000 hp delivered by the main transmission to be absorbed at the rotor head.

The NSH-3A rotating pushrods are replaced by an Alpha-1 couple modification kit. This consists of two short pushrods and an idler assembly, Figure 19, which changes the angle of the pushrod with respect to the blade horn. This results in a coupling effect which increases blade angle as the blade lags back in the power "on" condition and results in an increase in collective pitch range.

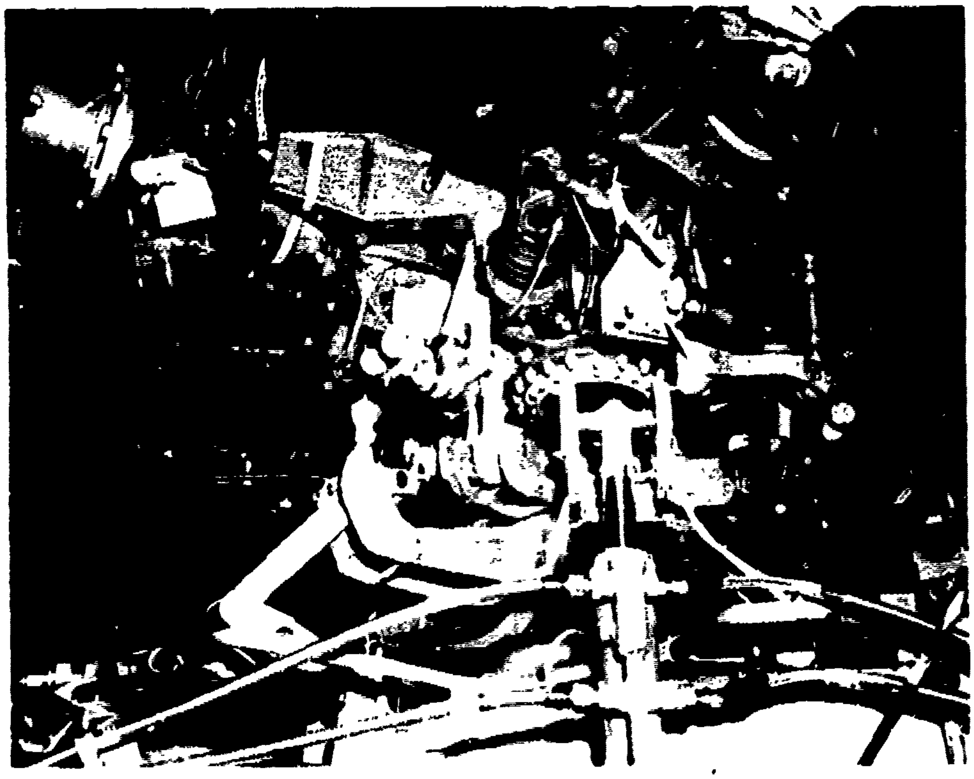

Figure 19. Alpha-1 Coupling, Rotor Head Modifications

FUSELAGE SYSTEM

Except to accommodate the YT58-GE-10 engines and the rotor control systems, no other major changes were made to the NSH-3A airframe. This airframe, which consists of large numbers of stringers, multielement frames, bulkheads, beams, spars and ribs, provides a highly redundant, failsafe structural design as is evident from the success of the S-61 type aircraft manufactured. The hardware used to physically fasten the aircraft to the tiedown pad is attached to the fuselage transverse frames below the main transmission (Figure 20). The center of rotor lift passes through the apex of the tiedown cables.

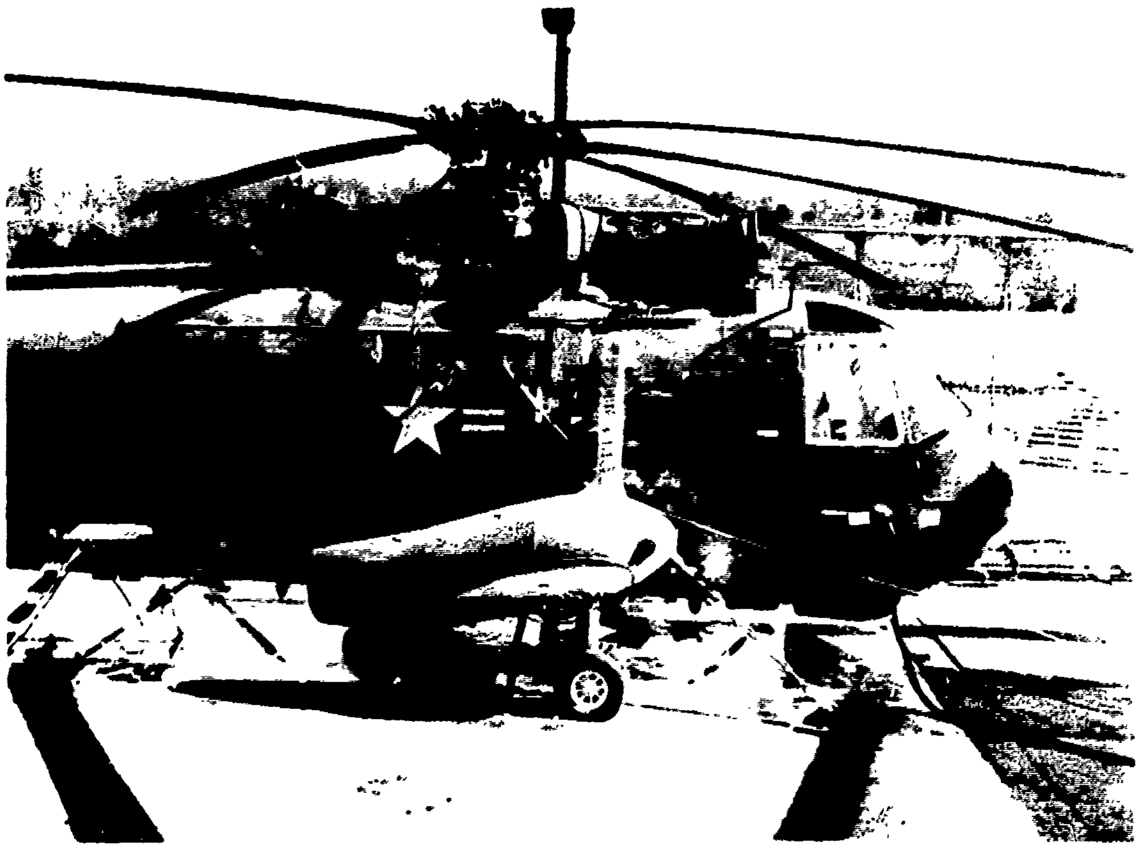

Figure 20. Aircraft Tiedown Fixtures

STATIC AIRCRAFT TESTING

To verify the adequacy of the aircraft, a series of static tests was conducted to ensure that modifications incorporated within the aircraft structure could withstand the design limit loads. The drive train systems were also subjected to vibration surveys to determine their natural frequencies.

CONTROL SYSTEM PROOF LOAD

The control system was subjected to a proof test whereby test loads were applied manually in the aircraft cockpit and reacted at the main rotor head. The loads, applied to the pilot's control stick, were measured on the copilot's stick through force gages. The pilot effort plus the force outputs of the auxiliary and primary servos was reacted by locking the main rotor release against pitch change motion with the pentagonal locking fixture encircling the main rotor head (Figure 21).

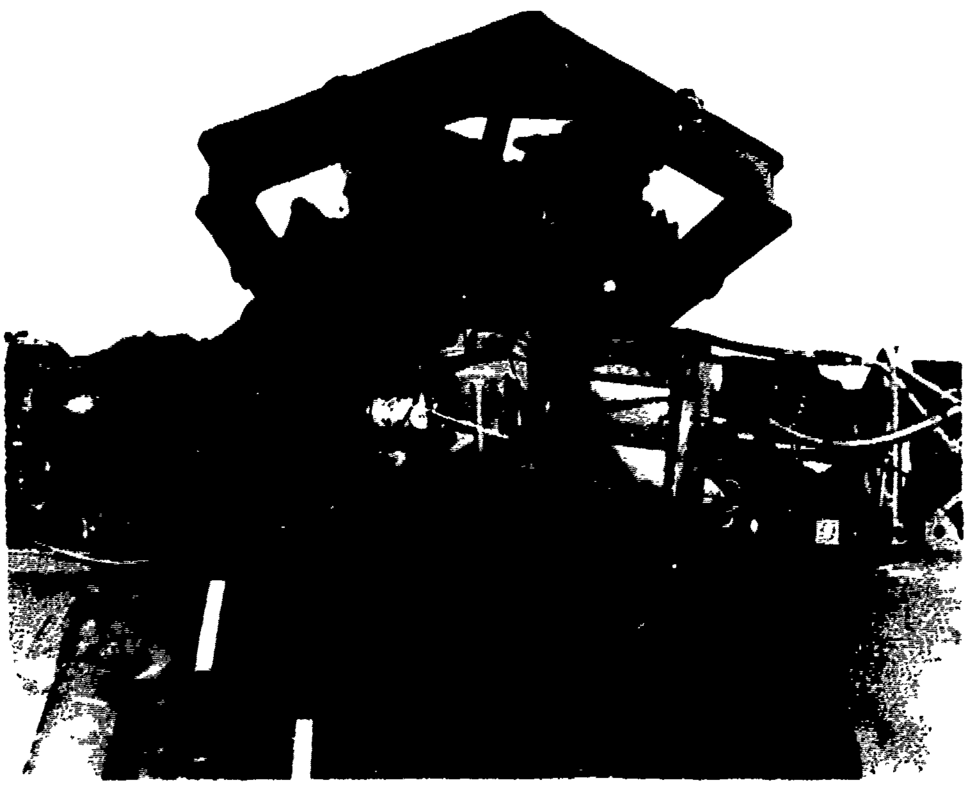

Figure 21. Proof Load Fixture, Rotor Head Control System

The tests were performed with the primary servo pressure both on and off. With the pressure off, the primary servo acted only as a mechanical link rather than a power boost unit; therefore, the control system between the auxiliary servo and primary servo input was more heavily loaded due to friction in this servo. The loads applied within the control system are shown on the schematic of Figure 18. Strain gaged and calibrated servo mounting pads, rotating pushrods, and control rods were monitored during testing to verify the calculated loads. As the control loads were cycled through their extreme positions, the system was checked for interference, binding and ratcheting.

HYDRAULIC SYSTEM PROOF PRESSURE TEST

Two independent hydraulic power boost systems were utilized within the flight control system. Each hydraulic system contained its own pump, reservoir, valves and supplementary components necessary to service the auxiliary servo system and primary servo system. The hydraulic pumps, located on the accessory gearbox, were powered by the tail rotor drive system; thus, hydraulic power from these pumps was available only when the main rotor was turning. To provide hydraulic power for ground checkout and system operation, an electric-motor-driven hydraulic pump was incorporated into the auxiliary hydraulic system. The suction line of this electric pump was plumbed into the reservoir and supply lines to the manifold assembly, shown in the aircraft hydraulic schematic of Figure 22.

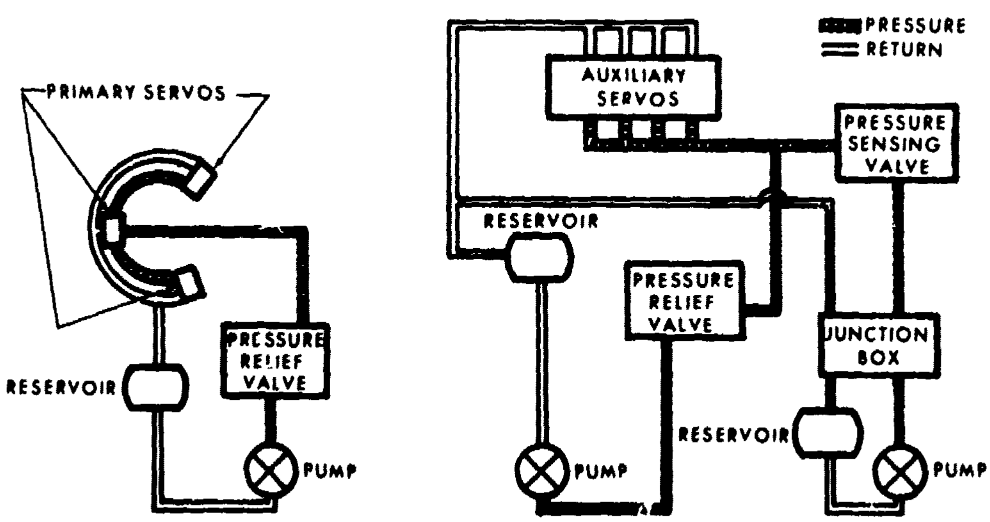

Figure 22. Aircraft Hydraulic System Schematic

From the manifold, the fluid was directed to the auxiliary servos, and a return line delivered the fluid back to the reservoir. The primary hydraulic pump delivered fluid directly to a line common with the three primary servos and hence back to its own reservoir.

The hydraulic plumbing and components were subjected to a test pressure of one and one-half times operating pressure for a period of two minutes in order to demonstrate circuit integrity.

ENGINE SHAKE TEST

Because of the complexity of the airframe-engine mounting system vibration modes, an engine installation shake test was conducted to determine if detrimental responses existed or if vibration levels exceeded the allowable limits. Vibration pickups, located at points designated by the engine manufacturer, enabled engine mode shapes and frequency response curves to be determined when excited by an electromagnetic shaker.

DRIVE SHAFT CRITICAL SPEED TEST

The natural frequencies of both engine output drive shafts, the oil cooler blower shaft, and first section of the tail rotor drive shaft were determined by conducting "rap" tests. This consisted of installing a vibration pickup to the midspan of the shaft, the output of which was recorded with a light beam oscillograph when excited by an external force applied to the shaft. The trace was the natural frequency in a decaying curve, which, when compared to a 60-Hertz reference trace, enabled the first critical mode of the shaft to be determined.

This data from the engine output drive shaft was used to support the engine shake test data. Overspeed operation of the YT58-GE-16 engine was 117 percent, and normal engine redline speed was 112.5 percent. The power turbine/drive shaft/input bevel pinion shafting configuration is shown in Figure 23. This was used to determine analytically the first bending mode of 26,669 rpm. The bending mode agrees with analytical computer studies conducted by General Electric in its "VAST" program.

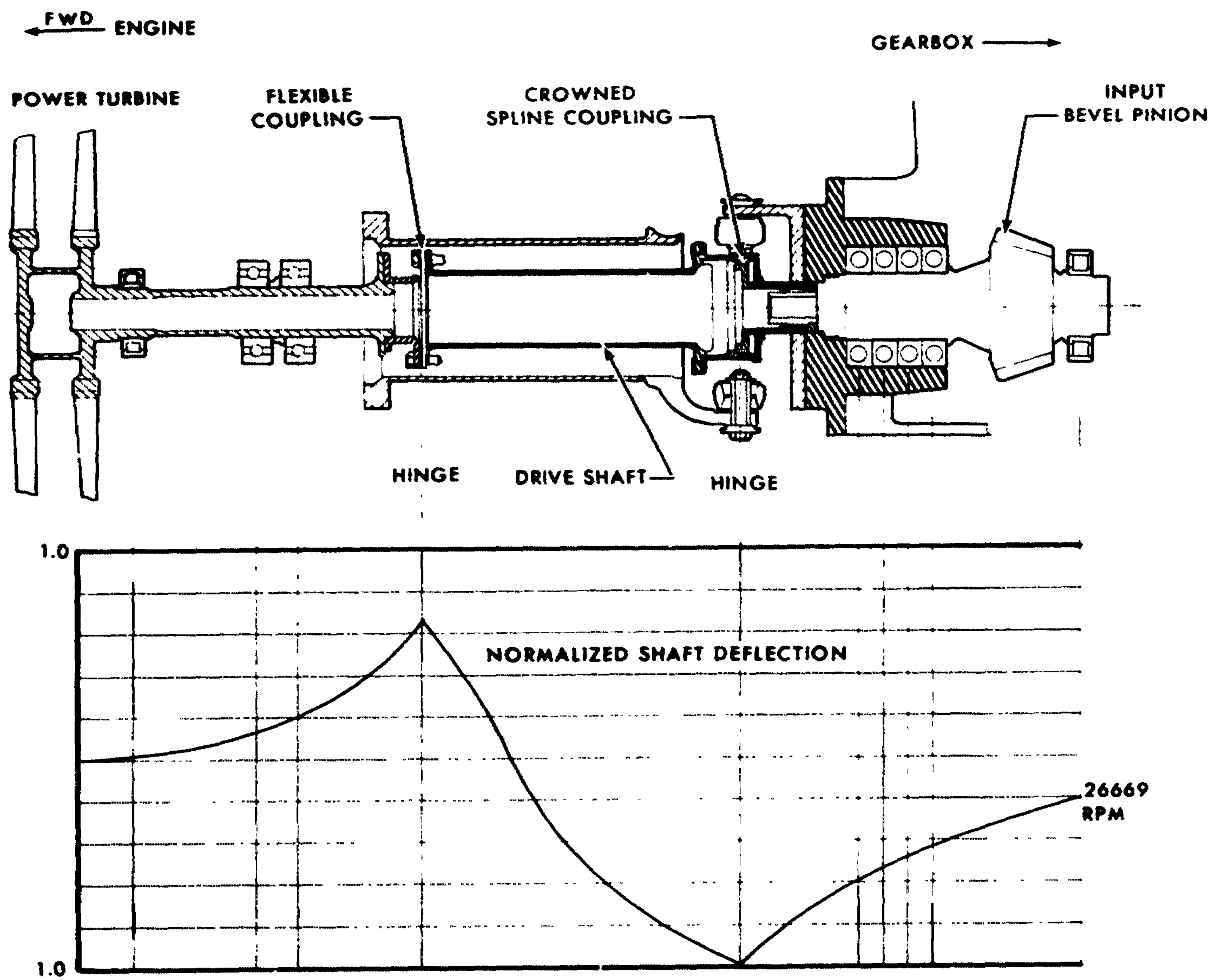

Figure 23. Input Drive Shaft Layout - Critical Speed Analysis

STATIC TEST RESULTS

All of the major objectives and requirements of the aircraft static tests were met. Several problems were discovered, as was the objective of the tests. These were resolved, and the aircraft was considered to be structurally adequate for tiedown testing.

Control System Proof Load

The controls were found to be structurally adequate to react pilot effort loads. Some problems were experienced with the system, including elastic buckling and deflections of the mixer supporting structure and slight interference of rod ends and bellcrank levers. These were resolved and a postest inspection was conducted. It was recommended that:

a. Usage of this control system be limited to the tiedown program until changes to eliminate the buckling are incorporated.

b. During tiedown, the structure supporting the mixer unit be periodically observed to ensure that no problems arise during operation.

c. At the completion of tiedown tests, the entire control system be completely inspected to ensure that no abnormalities are present in the system.

d. Operation of the control system with the primary servos shut off be minimized to reduce the loading of the system between the auxiliary servo output and primary servo input where the least buckling and deflections are present.

Hydraulic System Proof Test

The two independent circuits of the hydraulic system withstood the test operation pressure of 2,250 psi, which is equivalent to one and one-half times normal operating pressure, without leakage or deformation.

Engine Shake Test

The General Electric Company, manufacturer of the YT58-GE-16 engine, conducted the shake test and found no responses in the engine stator structure to indicate an engine operation vibration problem. However, a high-speed shaft response was found at 22,860 rpm (statically) on the right-hand engine and at 21,960 rpm on the left-hand engine. While these are zero-speed analysis conditions, the frequency is expected to be

higher during actual shaft operation. However, it was recommended that a careful scrutiny be made of the engine vibration levels in the overspeed region and that these shafts be field balanced as found necessary.

Drive Shaft Natural Frequency Test

It proved to be very difficult to "rap" the engine/transmission high-speed shaft. As can be seen from the drive shaft configuration of Figure 23, the drive shaft is enclosed within the torque tube. Table 5 lists the drive shafts tested and compares their natural frequencies with respect to normal operating frequency. All natural frequencies are well above the 125 percent of maximum operating range; the high-speed shaft, however, will be monitored during tiedown testing.

TABLE 5. DRIVE SHAFT NATURAL FREQUENCY TEST RESULTS

Shaft	Natural Frequency (cps)	Operating Speed (rpm)	Operating Frequency (cps)
Engine to Transmission High-Speed Shaft	2,500+	18,966	316
Transmission to Oil Cooler Blower Direct-Driven Shaft	275	7,031	117
First Section of Tail Drive Shaft	165	3,026	50
Second Section of Tail Drive Shaft	165	3,026	50
Tail Drive Shaft Between Intermediate and Tail Gearbox With Instrumentation Slipring	90	3,026	50

AIRCRAFT INSTRUMENTATION

The instrumentation installed on the aircraft for tiedown testing was used to monitor and assess the performance of the aircraft subsystems. As this was the first time the YT58-GE-16 engines were installed in an aircraft, they were extensively instrumented in order that General Electric could compare tiedown performance with laboratory test cell results. Strategic points on the airframe were monitored by measurement of strain gage output. The roller gear transmission and tail and intermediate gearboxes were monitored for temperature and vibration. In these gearboxes, excessive temperature and/or malfunction would curtail the test and warrant inspection.

ENGINES

The YT58-GE-16 engine as defined by the basic Military Specification MIL-E-8593 is supplemented by General Electric Model Specification E1005. Variations from MIL-E-8593 are the result of specific requirements for helicopter powerplants.

Performance ratings and associated shp's for the YT58-GE-16 engine are defined in terms of gas generation speed and power inlet turbine temperature. The military rating is obtained at maximum gas generator speed of 26,800 rpm and/or power turbine inlet maximum temperature of 815°C. The normal rating is obtained at a power inlet turbine maximum temperature of 785°C. Specification minimum horsepower ratings are defined at standard-day, sea-level-static conditions and are taken at the power turbine output shaft. They are 1,870 hp at military rating and 1,770 hp at normal rating.

The specification minimum horsepower is associated with a power turbine speed of 20,280 rpm. At any given gas generator speed and power turbine inlet temperature, the output power is essentially constant while the power turbine speed is within its normal operating range. Table 6 shows the engine performance summary for the YT58-GE-16 engine as published by the engine manufacturer. The table makes no allowance for helicopter installation for inlet and exhaust duct losses, for accessory power extraction, or for air extraction other than that required by the engine.

TABLE 6. YT58-GE-16 ENGINE PERFORMANCE RATINGS AT STANDARD-DAY, SEA-LEVEL-STATIC CONDITIONS

Rating	Min shp	Min Torque (in.-lb)	Max Gas Generator Speed (rpm)	Rated Power Turbine Speed (rpm)	Max Power Turbine Inlet Temp (°C)
Military (30 min)	1,870	5,815	26,800	20,280	805
Normal	1,770	5,504	-	20,280	785
90 Percent Normal	1,593	4,953	-	20,280	-
75 Percent Normal	1,328	4,129	-	20,280	-
Ground Idle	-	444 (max)	-	0	-

Ratings are at power-turbine output shaft. Torque is at rated power turbine speed. Max allowable operating speed of the power turbine is 21,275 rpm at no-load condition.

Gas generator speed (Ng), power turbine speed (Nf) and power turbine inlet temperature (T5) were monitored in the aircraft cockpit as well as in the control room.

Pickups (accelerometers) were located on both engines and torque tubes, as shown in Figure 11, to measure engine vibrations. These barium titanate accelerometers, insulated against electrical and temperature environment, were capable of measuring low frequencies excited by main rotor, tail rotor blade passage and low-speed shafting, etc., and high frequency emitted by high-speed shafting, engine rotors, reduction gearing, etc. In the YT58-GE-16 engine view of Figure 24 can be seen the power turbine crotch bracket on which is mounted a vibration pickup.

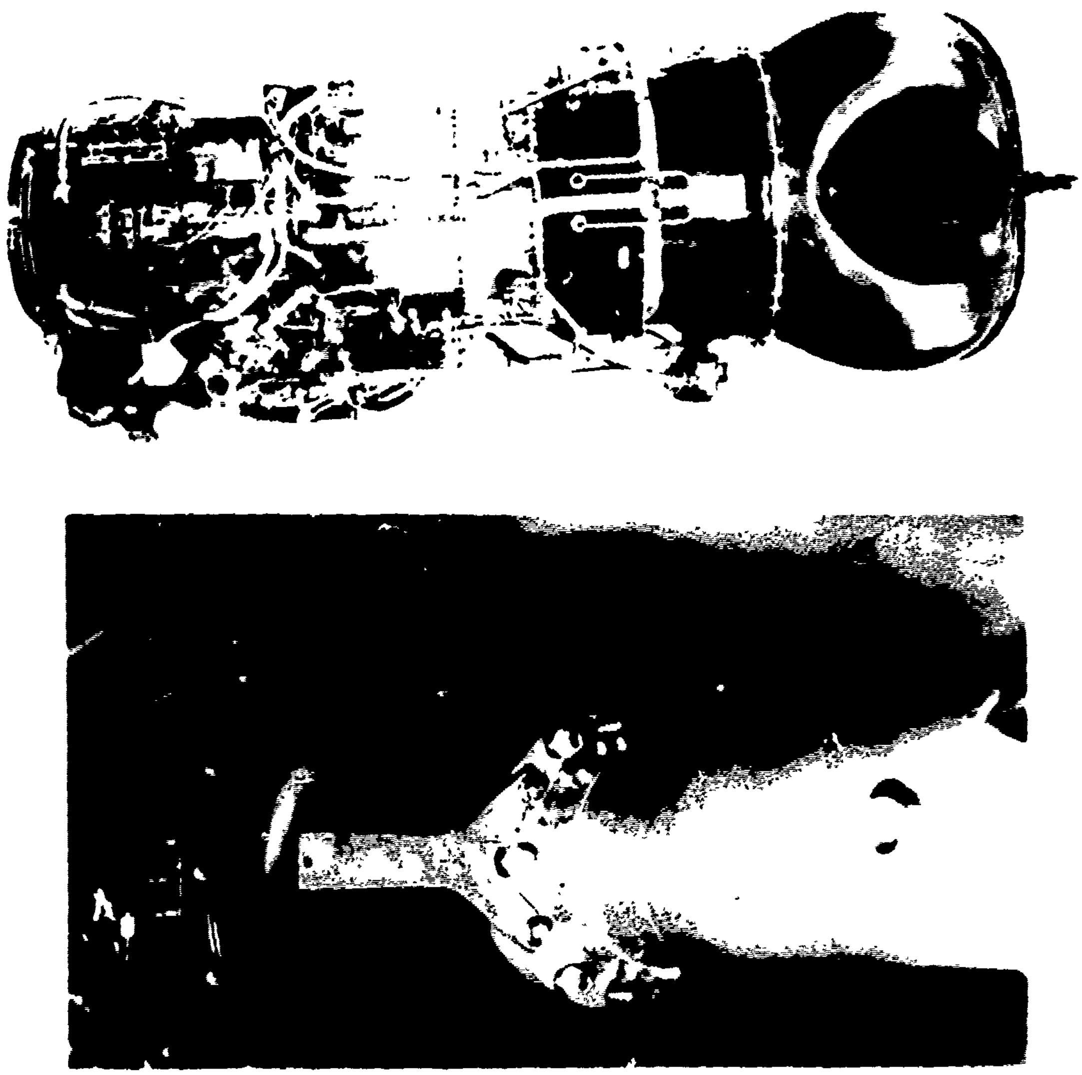

Figure 24. Vibration Pickup Locations, YT58-GE-16 Engine

ROLLER GEAR MAIN TRANSMISSION

The vibration pickups for the main gearbox were located as shown in Figure 25.

Thermocouples, located at all gearbox primary bearings, as shown in Figure 26 and tabulated in Table 7, were of the washer type. Lead wires from the thermocouple washers extended through gland fittings in the main housing to strip chart recorders in the control room. Also shown on Figure 26 are the locations of the main rotor shaft torque and bending bridge strain gages. These were used to measure the torque delivered to the main rotor head and the bending moments induced by the rotating main rotor blades. The strain bridges were calibrated by statically inputting known torques and bending moments into the main rotor shaft in the static calibration rig, Figure 27. Main rotor torque (NR) was measured as a percentage, with 100 percent torque equivalent to 3,000 hp transmitted at 203 rpm.

Lubrication oil sump temperatures and gearbox oil pressures were recorded in the aircraft cockpit as well as in the control room.

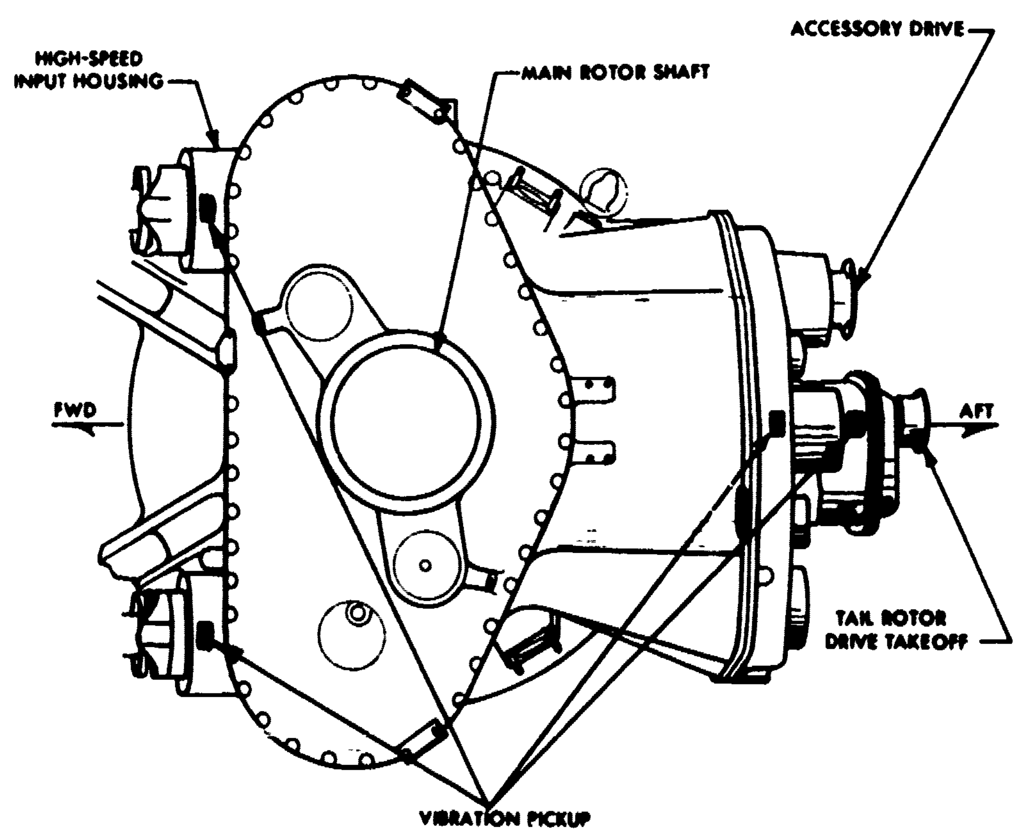

Figure 25. Vibration Pickup Locations, Main Transmission

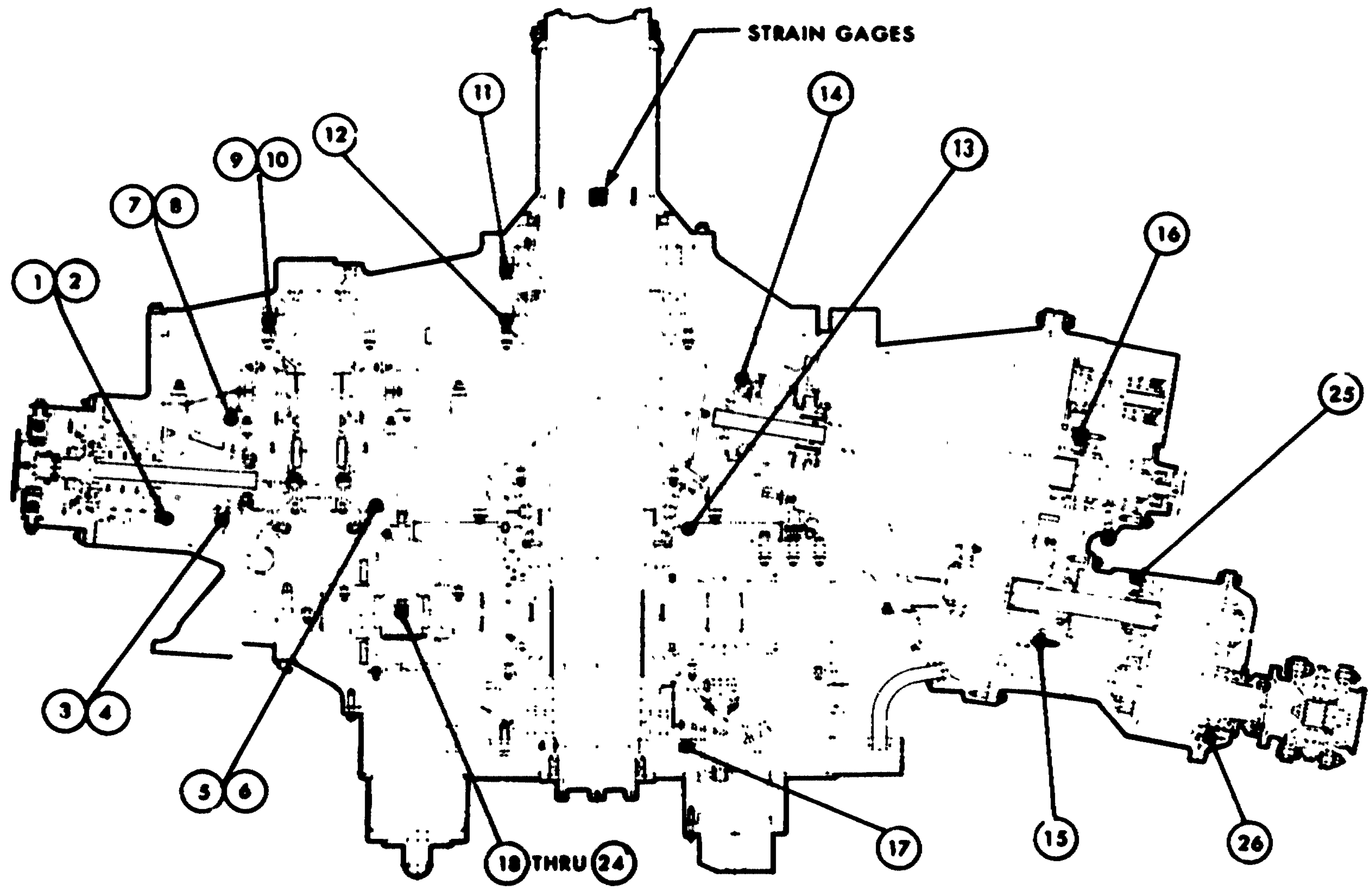

Figure 26. Thermocouple Locations, Main Transmission
(Numbers are keyed to Table 7)

TABLE 7. THERMOCOUPLE NOMENCLATURE, ROLLER GEAR TRANSMISSION

Number	Location
1	L.H. input bevel pinion stack ball bearings
2	R.H. input bevel pinion stack ball bearings
3	L.H. input bevel pinion stack ball bearings
4	R.H. input bevel pinion roller bearing
5	L.H. input bevel gear lower roller bearing
6	R.H. input bevel gear lower roller gearing
7	L.H. input bevel gear duplex bearings
8	R.H. input bevel gear duplex bearings
9	L.H. input spur gear upper roller bearing
10	R.H. input spur gear upper roller bearing
11	Main rotor shaft roller bearing
12	Outer shaft roller bearing
13	Outer shaft tapered roller bearings
14	Bevel pinion T.T.O. forward tapered roller bearing
15	Spur gear T.T.O. ball bearing
16	Spur gear T.T.O. roller bearing
17	Main rotor shaft duplex ball bearings
18	Second-row pinion spherical bearing
19	Second-row pinion spherical bearing
20	Second-row pinion spherical bearing
21	Second-row pinion spherical bearing
22	Second-row pinion spherical bearing
23	Second-row pinion spherical bearing
24	Second-row pinion spherical bearing
25	Adaptor gearbox input forward ball bearing
26	Adaptor gearbox output ball bearing
27	Lubrication "oil in" temperature
28	Lubrication "oil out" temperature

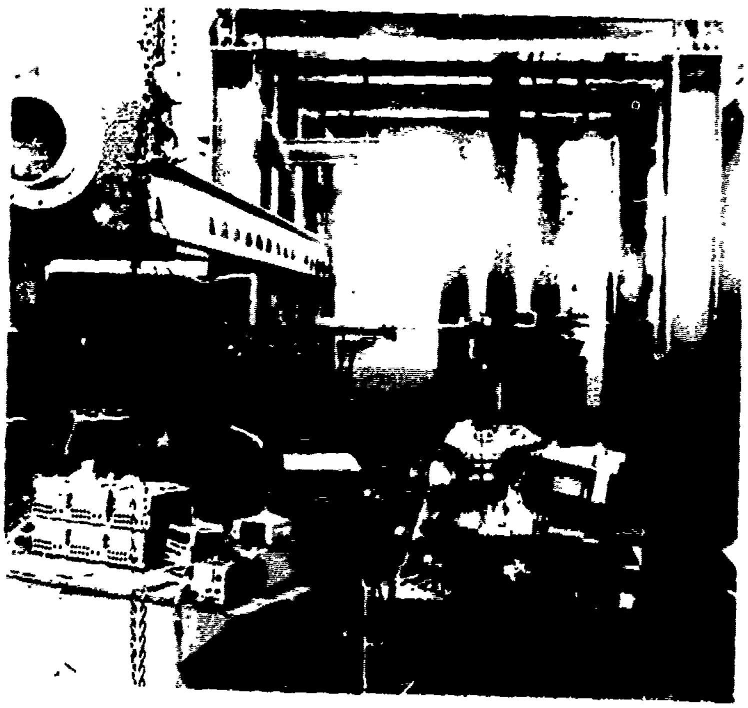

Figure 27. Static Calibration Rig, Main Transmission

GREASE-LUBRICATED TAIL AND INTERMEDIATE GEARBOXES

These test gearboxes are standard S-61 gearboxes modified for grease lubrication. The bearings are shielded to retain grease, yet still permit excess grease to be purged. Also, the gears themselves are shielded to retain grease around the gear teeth. Bayonet-type thermocouples are located at each bearing for temperature monitoring. In addition, two vibration pickups are located on the tail gearbox and one on the intermediate gearbox. A bulb indicator, set to light at 150°C, was installed in the cockpit to forewarn the cockpit personnel of tail and intermediate gearbox bearing overheating. Temperatures were constantly monitored in the control room. All vibration surveys were conducted in the control room.

ROTOR HEAD

The rotor head used for the roller gear aircraft, Figure 28, was a modified S-61 type grease-lubricated blade fold head. For the purpose of the tiedown test, the head was modified by locking out the blade fold mechanism and installing Alpha 1 couplings. These increased the collective range of the blades by mechanical linkage through the action of pushrods and levers. The pushrods were reciprocated in the plane of the main rotor shaft by the rotating swashplate, thereby oscillating the blade. The angle of the rotating swashplate was affected by the positions of the three 120-degree spaced primary servos operating on the stationary swashplate.

The S-61 rotor head is a well-proven, fully articulated system used normally to absorb power from two T58-GE-8B engines. These produce a combined input power of 2,500 hp, of which 2,300 hp is available at the main rotor system; the roller gear transmission delivers 3,000 hp to the same rotor system. To ensure structural adequacy of this system, critical components were strain gaged and monitored throughout the test. These included the rotating scissors which position the rotating swashplate. In Figure 28 can be seen the strain gage wires leading from bridges adhered to the stationary swashplate and the location of bridges on its restraining link, the stationary scissor.

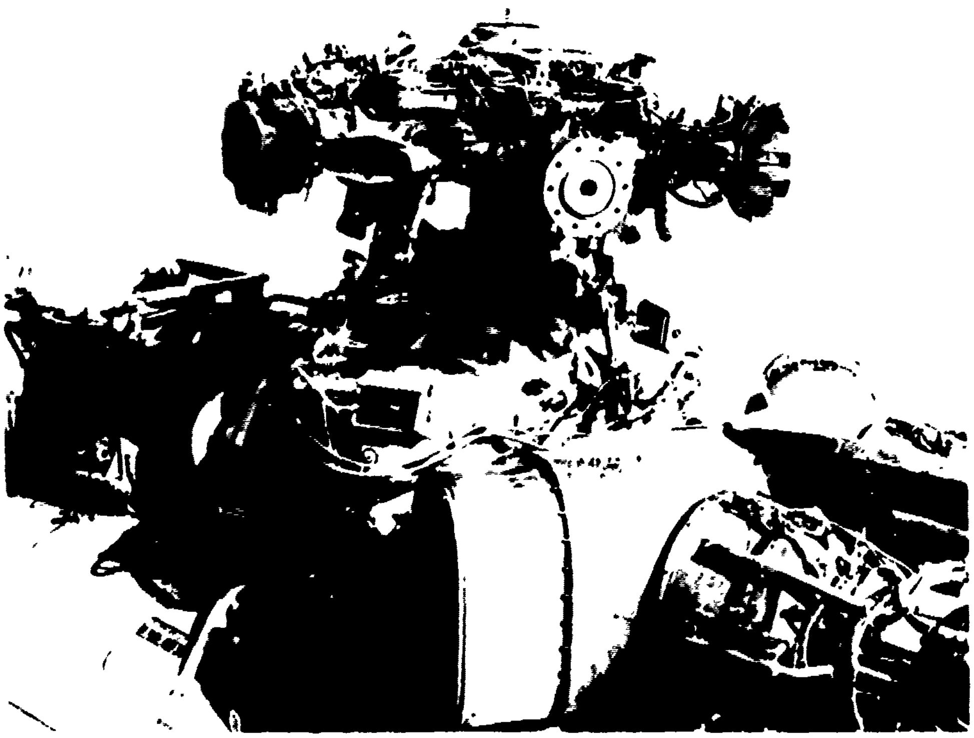

Figure 28. Rotor Head, Roller Gear Aircraft

AIRFRAME

The aircraft on which the roller gear transmission was mounted had an NSH-3A type S-61 airframe. This U. S. Navy version of the S-61 has provision for tail pylon fold. No major modifications to the stringers, multielement frames, etc., were made except for the fitting of the tiedown plate fixture.

The multielement redundant airframe structure designed to conservative static loadings provided adequate margin for fatigue loading. Tiedown testing, however, imposed severe strains on the airframe due to the in-ground-effect rotor downwash and the reaction of lift from the tiedown fittings. Severe buffeting of the aft fuselage structure occurred even when a hydraulic accumulator arrangement was fitted to the tail wheel. To measure the loads imposed on the tail pylon, the hinge fittings and tail cone frame at station 493, were strain gaged as shown in Figure 29.

The transmission was fitted to the airframe by an adaptor plate which allowed the 12-bolt fitting of the roller gear transmission to adapt to the 6-bolt fitting on the airframe. These transmission mountings, tied into frames at stations 290 and 243.5, were also strain gaged, as shown in Figure 29. The tiedown plate fitting was attached to these frames.

DATA ACQUISITION

The following documentation requirements were established for the roller gear tiedown test program.

TEST LOG

A test log was maintained in the control room. The log contained a chronological listing of significant events such as:

- Test Conditions
- Aircraft Time
- Test Times
- Engine Time and Starts
- Inspections
- Malfunctions
- Parts Replacement
- Adjustments
- Test Status Summary
- Witnesses' Signatures

TEST DATA

Test information was monitored and recorded during the tiedown test program by various methods, depending on the type of data required and the time frame in which it could be obtained.

Direct-Reading Indicators

Information from the aircraft instrument panel in the cockpit and from control room panel-mounted indicators was periodically recorded on data sheets. Information taken in this manner was as follows:

- Engine and Rotor Speeds, pct (Ng, Nf, and NR)
- Engine Temperature (T5), °C
- Engine Torque, pct
- Engine Fuel Flow (wf), lb/hr
- Engine Oil Pressure, psi
- Engine Oil Temperature, °C
- Main Transmission Oil Pressure, psi
- Main Rotor and Tail Rotor Torque, pct
- Rotor Controls Positions, deg
- Main Rotor Blade Lag Angle, deg
- Engine Vibration Levels, mils

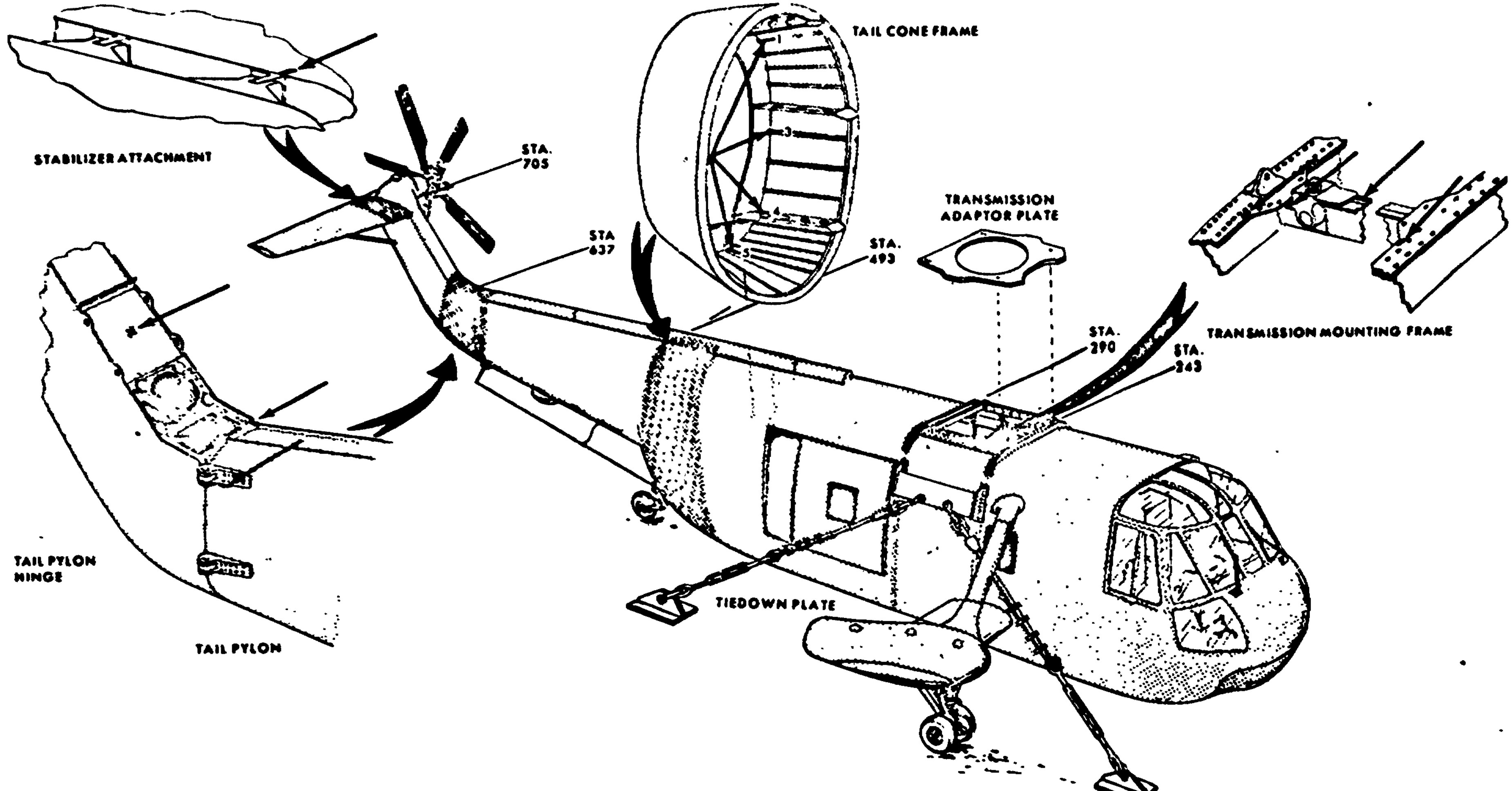

Figure 29. Strain Gage Locations, NSH-3A Airframe

Recorders

Two temperature recorders maintained a continuous operational record of 30 main transmission component temperatures, 20 engine component temperatures, and 10 temperatures of the tail and intermediate gearboxes. Periodic excerpts from the recorders were compiled on data sheets for comparative reference.

Two strip-chart recorders mounted in the control room provided a continuous record of main rotor shaft torque and of tail drive shaft torque.

Direct-Writing Oscillograph

Three direct-writing recording oscillographs were utilized to monitor airframe and component vibrations, control loads and stresses, and airframe loads and stresses.

Parameter Monitoring

During the roller gearbox tiedown test, the following parameters were monitored and/or recorded.

Visually Monitored Aircraft Cockpit Parameters

- Roller Gearbox Sump Temperature, °C
- Roller Gearbox Oil Pressure, psi
- Primary Servo Hydraulic Pressure, psi
- Auxiliary Servo Hydraulic Pressure, psi
- Rotor Speed (NR), pct
- Engine Free Turbine Speeds (Nf), pct
- Engine Gas Generator Speeds (Ng), pct
- Engine Interturbine Temperatures (T5), °C
- Engine Oil Temperatures, °C
- Engine Oil Pressures, psi
- Engine Fuel Flows, lb/hr
- Engine Torques, pct
- Outside Air Temperature, °C
- Collective Stick Position, deg
- Cyclic Stick Position, deg
- Pedal Position, deg
- Damper Lag Angle, deg

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Control Room Recorder Display

<u>No. 1 Engine Component Temperatures, °C</u>

Anti-Ice Valve
Ignition Box
Power Management System Amplifier
Start Bleed Valve
Flow Divider
Oil Cooler
Power Turbine Accessory Drive
Power Turbine Shaft (Nf)
T5 Harness
Fuel Pump

<u>No. 2 Engine Component Temperatures, °C</u>

Power Management System Amplifier
Stator Vane Actuator
Combustor Casing
1st Stage Turbine Casing
2nd Stage Turbine Casing
Compressor Casing 12 o'clock
Compressor Casing 3 o'clock
Compressor Casing 6 o'clock
Compressor Casing 9 o'clock
Exhaust Casing

Control Room Meter Display

<u>No. 1 and No. 2 Engine Vibrations, Mils</u>

Power Turbine Crotch Lateral
Power Turbine Crotch Vertical
Torque Tube Lateral
Torque Tube Vertical

Magnetic Tape Record

<u>No. 1 and No. 2 Engine Vibrations, Mils</u>

Front Frame Horizontal
Front Frame Vertical
Compressor Rear Frame
Turbine Casing Horizontal
Turbine Casing Vertical
Power Turbine Crotch Horizontal
Torque Tube Axial
Torque Tube Horizontal
Torque Tube Vertical

Control Room Oscillograph Display

<u>Gearbox and Aircraft Vibrations, Mils</u>

Pilot Seat Vertical
Pilot Seat Lateral
Roller Gearbox Left Input Vertical
Roller Gearbox Right Input Lateral
Roller Gearbox Rear Cover
Roller Gearbox Rear Cover Lateral
Roller Gearbox Rear Cover Axial
Roller Gearbox Tail Bearing Vertical
Cooler Shaft Vertical
Tail Gearbox Input/Horizontal
Tail Gearbox Output/Vertical
Intermediate Gearbox Input

Control Room Recorder Display

<u>Roller Gearbox Temperatures, °C</u>

Input Stack Bearing Left
Input Stack Bearing Right
Input Pinion Roller Bearing Left
Input Pinion Roller Bearing Right
Input Gear Roller Bearing Left
Input Gear Roller Bearing Right
Input Gear Housing - Duplex Ball Bearing - Left
Input Gear Housing - Duplex Ball Bearing - Right
Freewheel Roller Bearing Left
Freewheel Roller Bearing Right
Main Rotor Shaft Roller Bearing
Outer Shaft Roller Bearing
Outer Shaft Housing - Tapered Roller Bearing
Tail Takeoff Housing - Roller Bearing Forward
Tail Takeoff Drive Roller Bearing
Main Rotor Shaft Ball Bearing
Roller Gear Post Spherical Bearings (7)
Adaptor Housing Driver - Ball Bearing
Adaptor Housing Driven - Roller Bearing
Oil Cooler In
Oil Cooler Out

Control Room Meter Display

<u>Roller Gearbox Oil Flows, gpm and Pressures, psi</u>

Total Oil Flow
Pump Pressure
Main Manifold Pressure
Left Manifold Pressure
Right Manifold Pressure
Roller Gear Drive Inlet Pressure
Oil Cooler Out Pressure

Control Room Recorder Display

<u>Tail Gearbox Bearing Temperature, °C</u>

Input Outer
Input Inner
Output Inner
Output Middle
Output Outer

<u>Intermediate Gearbox Bearing Temperature, °C</u>

Input Outer
Input Inner
Output Inner
Output Outer

Control Room Display/Recorder

Main Rotor Shaft Torque (chart recorder)
Main Rotor Shaft Bending (oscilloscope)
Tail Rotor Shaft Torque (chart recorder)
Barometric Pressure (meter)

Control Room Oscillograph Display

<u>Flight Control System Loads</u>

Rotating Scissors
Rotating Pushrod
Stationary Scissors
Stationary Swashplate
Control Rod - Primary Servo Input

Main Gearbox Mount Stress

Transmission Rear Frame - Right
Transmission Rear Frame - Lower
Transmission Rear Frame - Inboard
Transmission Forward Attachment

Tail Pylon Stress

Tail Pylon Hinge - Top
Tail Pylon Hinge - Aft
Tail Pylon Hinge - Top Left
Tail Pylon Hinge - Bottom Left
Stabilizer Attachment - Top
Stabilizer Attachment - Bottom
Tail Cone - 5 o'clock
Tail Cone - 4 o'clock
Tail Cone - 3 o'clock
Tail Cone - 1 o'clock

TIEDOWN TEST FACILITY

The tiedown facility consisted of an asphalt-covered area containing an integral steel reinforced concrete pad in which cable tiedown fittings were embedded. A multilayered steel wire fence partially enclosed three sides of the test pad area. A blockhouse type control room was located on one side, from which test personnel viewed the test area through an impact-resistant window. Figure 30 shows the tiedown area as viewed from outside the control room. Boxed channels running from the control room to the aircraft contained instrumentation cables which connected aircraft instrumentation with the control room.

Control Room

The facility control room housed the majority of the test data acquisition equipment and provided the working area for test personnel. Figure 31 shows the magnetic tape, oscillograph and recorder equipment used, as well as instruments and meters used for real-time monitoring of the test program. Additional instrumentation was located in the test aircraft for use by the aircraft operators.

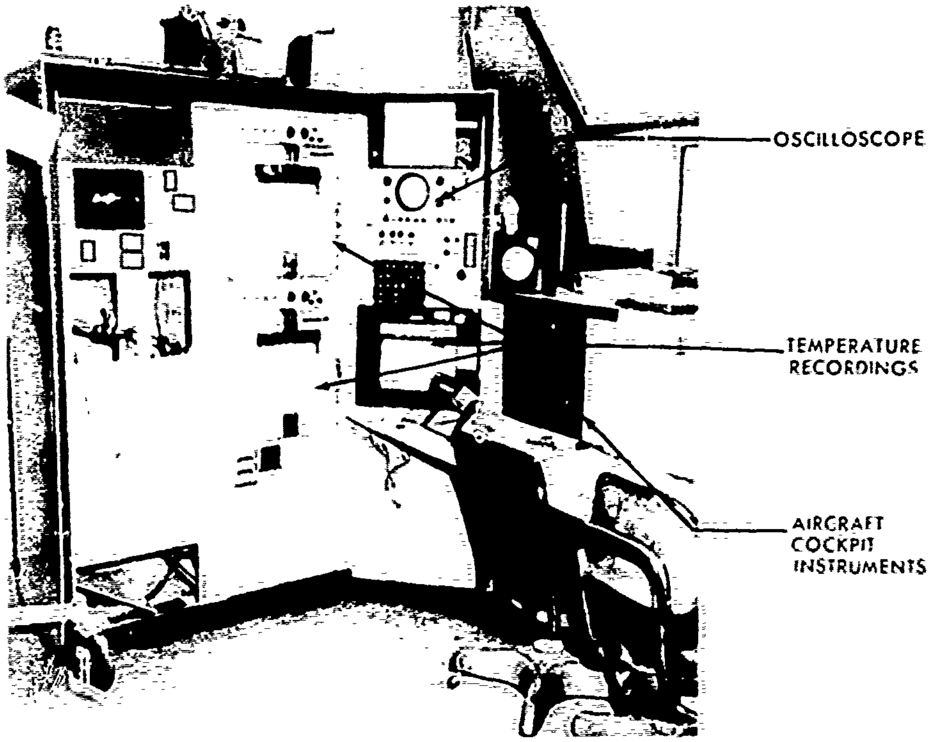
An intercom system provided voice communication between control room and aircraft personnel; in addition, the aircraft crew maintained radio voice communication with the control tower.

Aircraft Cockpit

The S-61 aircraft provided for side-by-side seating of the pilot and copilot. The primary flight instruments were duplicated at each seat position and were located on the seat centerline (Figure 32). The engine and transmission instrumentation was located in the center of the console for monitoring by either pilot. This display included gas generator tachometer (Ng), power turbine inlet temperature (T5), engine oil pressures, transmission oil pressure and hydraulic pressures.

The bottom center section of the instrument panel contained collective and lateral stick positions, pedal and damper lag positions.

Figure 30. Aircraft, Tiedown Test



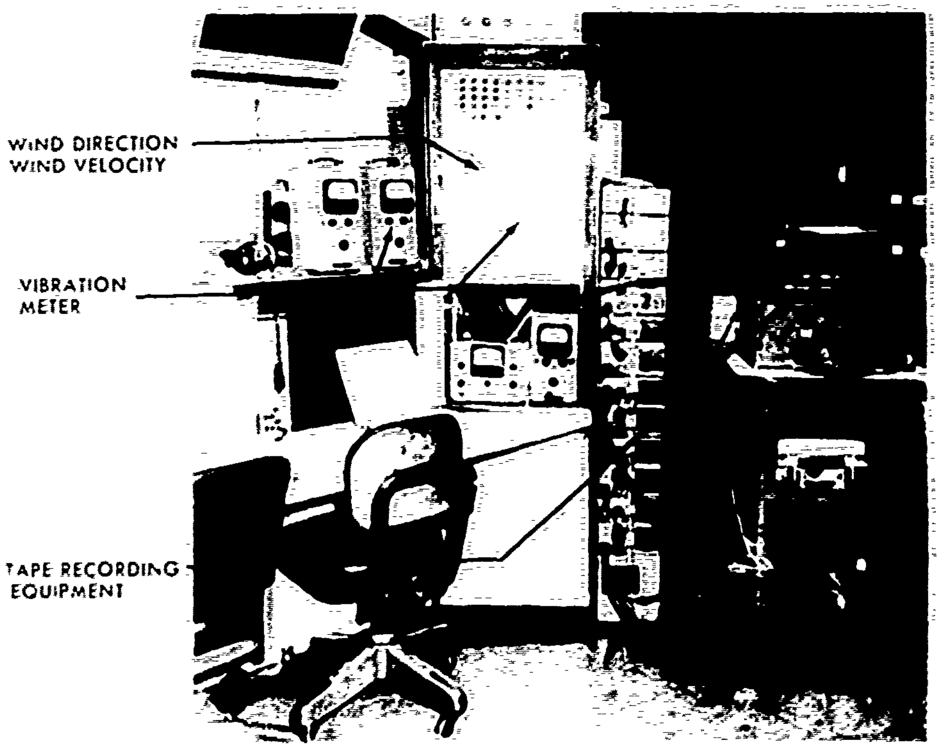


Figure 31. Data Acquisition, Tiedown Facility Control Room

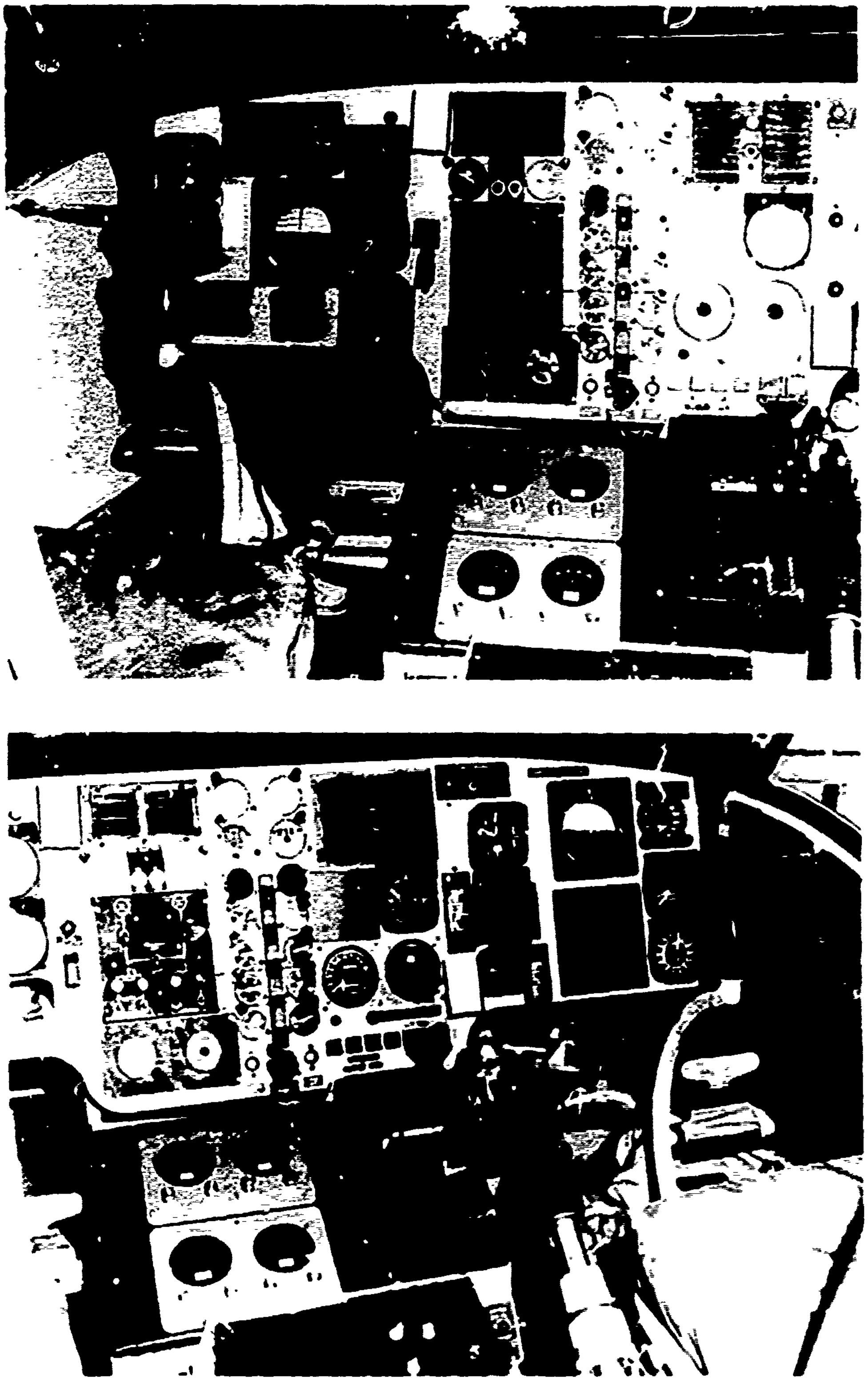


Figure 32. Aircraft Cockpit Instruments

OPERATING PROCEDURE

Although the aircraft is restrained to the ground with cables, it is operated as a flight aircraft and is maintained and inspected in a condition of "flight readiness". This section presents the tiedown test procedures which were used in the roller gear tiedown test program.

The test aircraft and the test facility were subject to periodic quality control inspections. "Postflight" inspections were conducted to discover any damage or discrepancy on the test aircraft which may have developed during the inspection interval of 5 test hours or 5 calendar days, whichever was shorter.

A "preflight" inspection was conducted to determine if the aircraft was ready for each day's run. A "walk-around" inspection was conducted prior to any test run.

Safety Review

Prior to any operation of the test aircraft and subsequent to installation of the aircraft on the tiedown pad, an area safety review was conducted. Any discrepancies were corrected prior to first test runs.

Emergency Procedures Review

Prior to first run of the test aircraft, the qualifications of the crew in emergency procedures were reviewed and any required training was carried out. A review of emergency procedures for the specific aircraft under test was conducted, attended by all cognizant test personnel, crew, engineers and pilots.

Prerun Briefing

Prior to each test run, the cognizant test engineer conducted a briefing attended by the pilots and crew. The following items were typically discussed:

1. Posttest observations from previous runs
2. Aircraft changes since last run
3. Emergency procedures
4. Immediate test plans
5. Possible test problems - resolution methods
6. Data acquisition points
7. Quality control requirements

Aircrew Utilization

The aircraft was initially operated by qualified pilots at both the pilot's and copilot's stations. After the initial engine starts, overspeeds, and first power runs were completed, the aircraft was operated with one qualified pilot at the pilot's station, handling engine and rotor controls, and a qualified assistant at the copilot's station to monitor cockpit instruments and to assist in securing the aircraft systems in the event of an emergency.

Aircraft Operation

The test aircraft was maintained, inspected, and operated using standard flight test procedures. The starting, rotor engagement, shutdown, and emergency checklists, based on standard S-61 checklists, were modified to suit the roller gear aircraft and the tiedown test program. Standard wind limits for rotor engagement and operation at high tail rotor power were strictly observed. These wind speed and direction limits are shown in Figure 33.

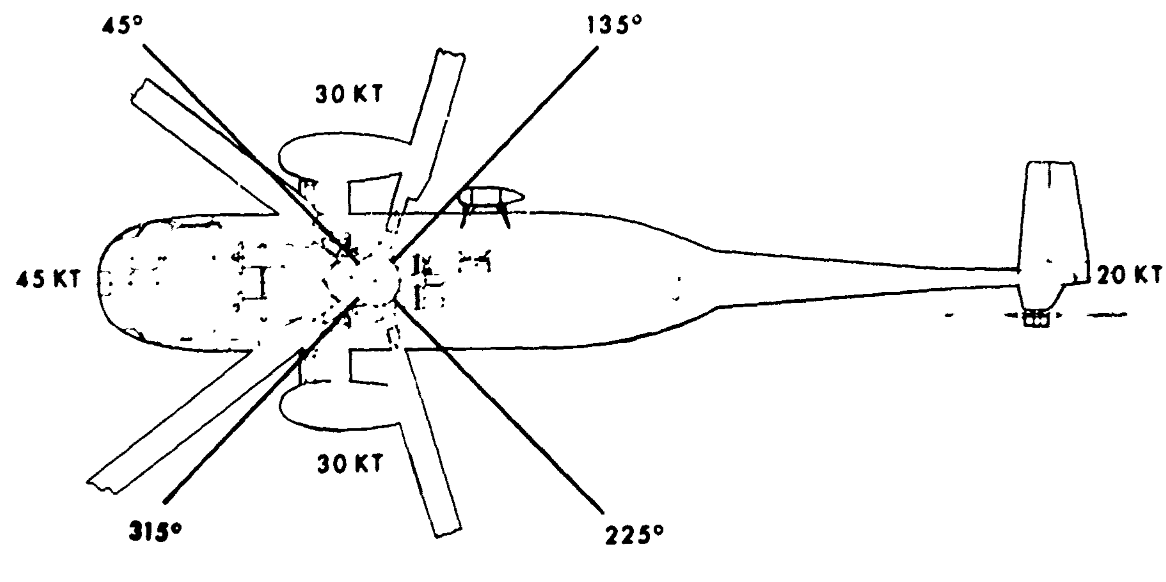


Figure 33. Wind Direction Limits, Aircraft Operation

AIRCRAFT TIEDOWN TEST

The following pages list the tests conducted on the roller gear tiedown aircraft. For these tests, the helicopter was ballasted to a maximum gross weight of 19,100 lb by securing sandbags on the cabin floor at the aircraft center of gravity. The helicopter was restrained to the tiedown pad by proof-tested cables and the tail wheel was secured by attachment to a hydraulic accumulator. The helicopter instrumentation and communication systems were connected to the control room, the fuel tanks were filled to capacity, and initial inspection accomplished. The main rotor blades were not installed for the initial tests in order to reduce rotating inertia for better control and feedback response.

INITIAL TESTS

Initial Engine Starting

As the YT58-GE-16 engines are not in service, the General Electric Company asked for specific engine data relating to starting cranking rpm, time to engine light-off, maximum transient temperature at T5, and starter drop-out rpm. As each engine was started individually and allowed to run at ground idle against the rotor brake, thereby not allowing rotation of the engine output drive shaft, the above data was recorded. During the initial starting and operation of Number 2 engine (right-hand location), the fuel flow divider, shown in Figure 34, leaked fuel externally. This divider had to be replaced.

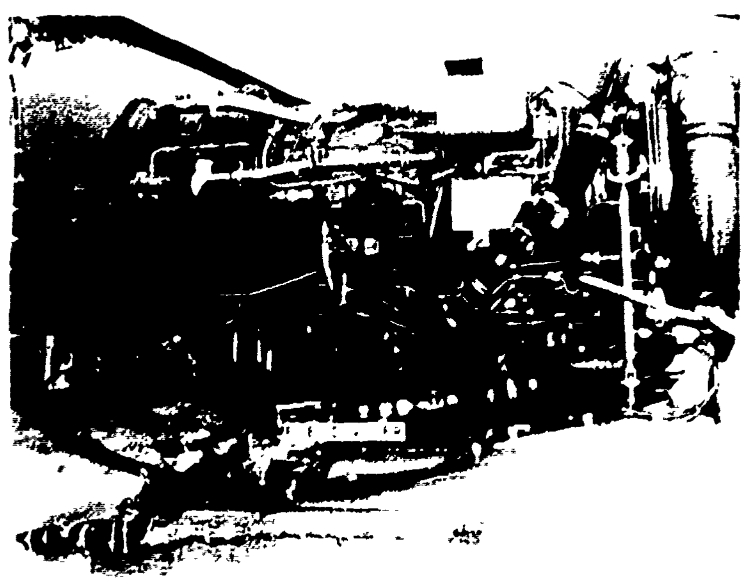


Figure 34. Fuel Divider, YT58-GE-16 Engine

Initial Drive-Train Tests

The following tests were also accomplished without main rotor blades installed, the S-61 rotor head and blades having previously been fully qualified for operation to 117 percent speed. Tail rotor blades were installed.

A normal Number 1 engine start and rotor engagement were made, and a vibration record was obtained of the engagement and run-up to 100 percent rotor speed. All instrumentation was checked out and a complete set of data was obtained. After stabilization, a normal shutdown was conducted and the aircraft was inspected.

In order to verify resonance-free operation of all drive-train shafts up to the autorotative redline speed of 117 percent, it was necessary to drive the rotor with the engines over their normal redline of 112.5 percent.

The stops on the engine speed selector/fuel control, Figure 35, were removed for this test. The rotor was slowly accelerated from 100 percent to 112.5 percent while vibration data was monitored and then was accelerated, as quickly as could be done smoothly, from 112.5 percent to 117 percent and back again - on the order of 5 seconds overspeed for each engine. Satisfactory operation of drive shafts was then determined by examination of data to find any damaging vibration "peaks" or excessive increase in vibration with speed up to 117 percent rotor speed. Data was examined from the engine drive shafts, the oil cooler blower shaft, and the first section of the tail drive shaft. Engine vibration survey records were examined to determine if any engine pickup registered vibration in excess of 3 mils steady state and 5 mils transient (G. E. limits) up to 112.5 percent rotor speed.

The rotor blades were then installed for the remainder of the tests.

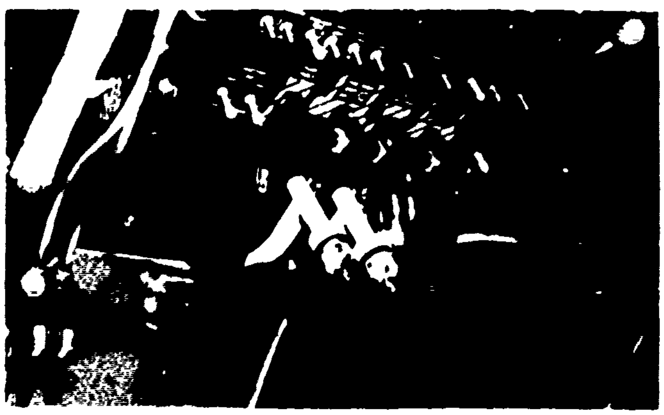


Figure 35. Engine Speed Selector Controls, NSH-3A Aircraft

First Power Runs

With main rotor blades installed, the 5-hour spectrum, Table 8, was run. Initial starts, engagements, and applications of power were closely monitored for proper functioning of all systems, load sharing of the tiedown cables, and any evidence of possible problems. Data records were obtained at the beginning and end of each condition.

TABLE 8. 5-HOUR BREAK-IN SPECTRUM.

Time (hr)	Total Main Gearbox Input (hp)	Tail Rotor Power (hp)
1	Flat Pitch	Neutral
1	1,000	100
1	2,000	250
1.5	3,000	350
0.5	Maximum Ratings *	375 **

* Maximum ratings are: 3,740 hp total input, 3,000 hp main rotor, 1,870 hp each engine, 814° T5, and 102.2 percent Ng. Power is increased until one or more of the ratings are reached.

** Tail gearbox endurance limit.

Power-Train Response Tests

Normal engine starts and rotor engagement were made. A dual-engine power condition of 2,200 total horsepower at 100 percent NR was established for power train response tests, the Number 2 engine speed selector was locked in position, and the Number 1 speed selector was moved up and down while the reaction of NR, Nf, Ng and T5 was observed. The selector was moved slowly at first and then more rapidly as engine and rotor response were determined. Particular attention was paid to any unusual delay or sensitivity of the speed selector/engine/rotor response. Overshoot of Nf relative to NR was noted. The Number 2 speed selector operation, with the Number 1 lever locked, was checked as in the foregoing tests. The power-train response of both speed selectors operating simultaneously was deleted because of the extreme sensitivity of the speed selectors.

ENDURANCE TEST

The 50-hour endurance test, designed to test the roller gear transmission and evaluate its compatibility within the overall helicopter, was run in five 10-hour cycles as listed in Table 9. The power spectrum was generally in accordance with military specification MIL-T-8679. The takeoff, military and normal ratings are defined in Table 6.

During the test, the cyclic and directional controls were cycled 15 times per hour to their extremes during the normal rated power (NRP) runs. At other times, they were held fixed in either cruise position or vertical ascent position, whichever was appropriate for the power level being run. Operation of the roller gear transmission freewheel unit and rotor brake was checked six times per hour during the takeoff portion of the test, thereby accumulating a minimum of 60 operations throughout the test.

During one of the 10-hour endurance cycles, the normal vibration pickups on the rear cover were replaced with accelerometers which drove a high-frequency-response oscillograph system. At each of the power conditions of a 10-hour endurance cycle, a vibration record was made of the rear cover vibration character.

The roller gear transmission and other aircraft dynamic components were visually inspected at suitable intervals throughout the test program. Figure 36 shows the NSH-3A aircraft equipped with the roller gear transmission on the tiedown pad.

TABLE 9. ENDURANCE TEST, 10-HOUR CYCLE

Test Condition (Per MIL-T-8679)	Time (hr)	MGB Input (hp)	Rotor Speed (%)	Torque Main Rotor (%)	Torque Tail Rotor (%)	Note
Takeoff	1	3,540/Idle	100/Idle	102/Idle	63/Idle	1
Military	1	3,700/2,120	100	107/60	63/36	2
Normal Rating	3	3,540	100	102	63	3
90% Normal Rating	1	3,190	100	92	57	4
80% Normal Rating	1	2,830	100	81	50	4
60% Normal Rating	1	2,120	91	66	40	4
Overspeed	1	3,540	110	93	58	4
Single Engine	1	1,870	100	52	31	5

Notes:

1. "Takeoff" is a 1-hour period of alternate runs of 5 minutes at takeoff power and 5 minutes with both engines at ground idle after applying and releasing the rotor brake during the first minute of the idle run.
2. The "military power" test condition is a 1-hour period with the controls positioned for "vertical ascent" at military power for the first 30 minutes and with the controls held in "cruise position" at 60% normal rating for the remaining 30 minutes.
3. The "normal rating" test condition covers a 3-hour period. Fifteen times each hour the main rotor cyclic control and the directional controls are positioned and held for 10 seconds each at forward, aft, left, and right. Control deflections do not exceed those encountered in formal flight.
4. Continuous operations with controls held in "cruise" position.
5. Single-engine operation - 30 minutes each engine per 10-hour cycle.

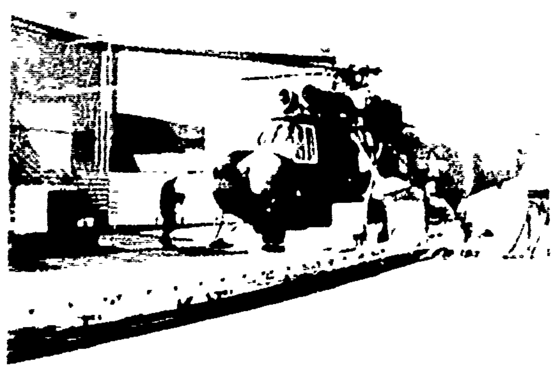


Figure 36. Roller Gear Tiedown Aircraft

TIEDOWN TEST RESULTS

This chapter discusses the tiedown test to which the roller gear aircraft was subjected. During this test program, a total of 57.6 hours of rotor turning was logged. All major requirements of the test plan were met. A chronological summary of significant events is shown in Figure 37.

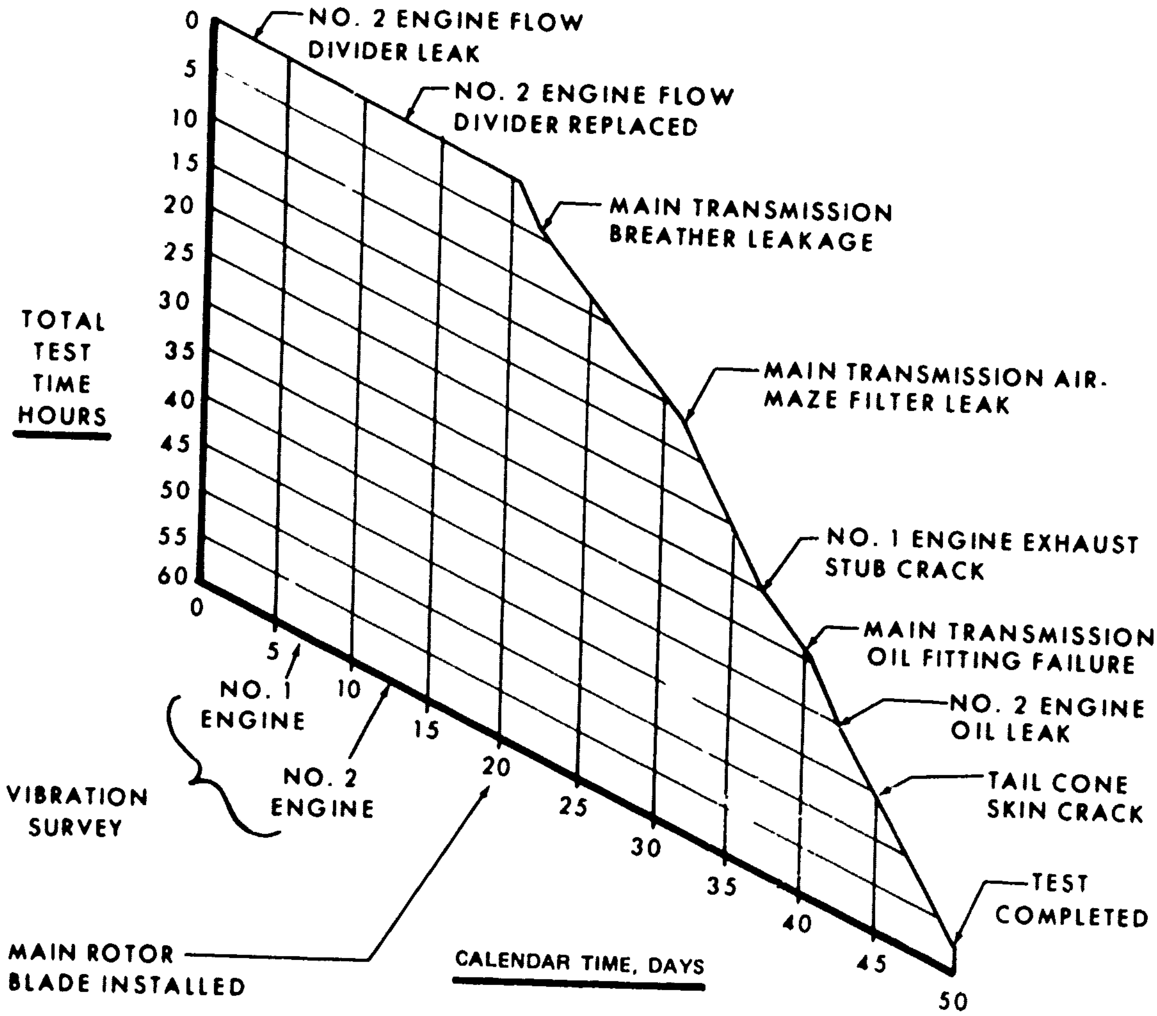


Figure 37. Chronological Summary, Roller Gear Tiedown Test

Actual Power Spectrum

The total rotor turning time of 57.6 hours exceeded the 50-hour test requirement; however, the actual power levels applied were less than planned due to engine performance degradation, primarily attributable to "hot-day" conditions. The actual test conditions applied are shown in Tables 10 and 11 for the 5-hour break-in test and endurance test, respectively. This information is further broken down and listed in terms of actual power levels in Table 12.

During the "military power" test condition, which consisted in part of 30 minutes at maximum rated power (30-minute rating), the actual power level obtained average 3,370 hp, or an average loss of 330 hp from the planned level of 3,700 hp. This lower power level was obtained when turbine temperature limits, T5, were reached.

The reduction in the planned power levels in normal rated power (maximum continuous power) amounted to an average of 310 hp, from 3,540 hp to about 3,230 hp. This power loss was noted when the maximum continuous engine temperature limits were observed. The required power levels were obtainable for the 90 percent normal rated power and 80 percent normal rated power runs.

During the 60 percent normal rated power test condition, the required rotor speed of 91 percent was below the normal governing range of the YT58-GE-16 engines. The first hour of this condition was conducted at the 91 percent rotor speed by operating on "emergency" throttles. However, the high level of airframe vibration precluded further operation at that condition. Subsequent 60 percent NRP test conditions were conducted using the speed selectors in governing range, 93-94 percent rotor speed.

When the "overspeed" endurance test condition was run, two problems were encountered which reduced the actual power level from the planned power level. First, with the engine controls at the maximum stop, the rotor speed was 112 percent in flat pitch. Engine droop characteristics then prevented the application of high power at the required high speeds. Second, the maximum continuous engine temperature limits were reached at about the same point. The test condition was then run at 109-110 percent rotor speed at an average of 2,820 hp, an average loss of 720 hp from the planned level of 3,540 hp.

Single-engine maximum power was also unobtainable. The reduction in planned power levels amounted to an average of 180 hp, from 1,870 hp to 1,690 hp, in Number 1 engine and an average of 190 hp, from 1,870 to 1,680 hp, in Number 2 engine when the engine 30-minute gas generator speed and temperature limits were observed.

Operational Problems

During monitoring of Number 2 engine, a fuel leak occurred at the interface between the flow divider and the engine supply port. This engine was repaired with a modified flow divider and new fuel control. No problem with flow divider leaks was encountered during the remainder of the test.

After 33.8 hours of test, Number 2 engine began to leak oil from an air scavenge line. General Electric approved operation of this engine for the remainder of the test.

At 26.9 hours test time, the exhaust stub of Number 1 engine developed a 2- to 3-inch horizontal crack on the top aft inboard edge. This crack was welded and no further problem was encountered.

Each of the engines was initially equipped with "experimental" fuel control units for investigation of performance. In early test programs, the speed selectors were determined to be too sensitive in some ranges of operation. When the Number 2 flow divider was being repaired, a "production" fuel control was installed on this engine. Some sensitivity problems still existed, and measurements were made of fuel control speed selector input shaft position as a function of power. These results, shown in Table 13 and plotted in Figure 38, indicate that Number 2 engine is very sensitive right up to maximum power and that both engines are sensitive in the low power area.

Some evidence of engine torque tube/transmission gimbal mount rubber damage was noted at 28 test hours. This may be due to the vibration in that area and/or degradation from gearbox oil breather leaks.

The engine drive shafts were equipped with a phase-displacement type of torquemeter system where a magnetic pickup senses shaft windup by relative displacement of two pole pieces. Due to the stiffness in the drive shafts, total windup is small and the system did not function satisfactorily until near the end of the test. Power measurement and power matching of engines without the engine torquemeters is possible since main and tail rotor torques were used as a measure of power and the engines matched by using T5 and Ng.

TABLE 10. 5-HOUR BREAK-IN TEST POWER LEVELS

Test Condition	Total Main Gearbox Input (hp)	Main Rotor Torque* (%)	Main Rotor Power (hp)	Tail Rotor Torque** (%)	Tail Rotor Power (hp)	Frictional Losses and Accessory Power (hp)	Drive Train Speed*** (%)	Time (hr)
Maximum	3,390-3,440	98-100	2,940-3,000	55-60	311-339	135	100	.5
3,000 hp	3,110-3,480	89-100	2,670-3,000	55-62	311-350	133-135	100	1.6
2,000 hp	2,130-2,410	60- 67	1,800-2,010	36-48	203-271	128-129	100	1.3
1,000 hp	1,080-1,370	33- 38	990-1,140	17-18	96-102	122-123	100	1.7
Flat Pitch	490	11	330	7	40	118	100	4.8

* 100% Main Rotor Torque = 3,000 hp (77,312 ft-lb at 203.8 rpm).
** 100% Tail Rotor Torque = 565 hp (979 ft-lb at 3,030 rpm).
*** 100% Drive Train Speed = 18,966 rpm Engine Drive Shaft, 203.8 rpm Main Rotor, 1,243 rpm Tail Rotor

TABLE 11. ENDURANCE TEST POWER LEVELS

Test Condition	Total Main Gearbox Input (hp)	Main Rotor Torque* (%)	Main Rotor Power (hp)	Tail Rotor Torque** (%)	Tail Rotor Power (hp)	Frictional Losses and Accessory Power (hp)	Drive Train Speed*** (%)	Time (hr)
Takeoff High	3,080-3,600	89-105	2,670-3,150	45-65	254-367	133-136	100	2.5
Takeoff (Idle)	100	5	60	5	10	30	40	2.5
Military High	3,290-3,740	91-109	2,730-3,270	51-60	288-339	133-138	100	2.1
Military Low	2,120-2,350	60- 67	1,800-2,010	35-41	198-232	128-129	100	2.7
100% NRP	2,976-3,590	85-105	2,550-3,150	47-60	266-339	132-136	100	14.9
90% NRP	3,120-3,280	88- 94	2,640-2,820	49-58	277-328	133-134	100	3.9
80% NRP	2,810-2,940	80- 83	2,400-2,490	47-62	266-350	131-132	100	3.5
60% NRP	1,960-2,250	60- 70	1,630-1,970	35-41	180-218	127-129	91- 94	4.0
Overspeed	2,490-3,020	62- 80	2,010-2,640	38-55	232-342	129-132	108-110	4.0
Single Engine No. 1	1,640-1,750	45- 48	1,350-1,440	28-32	159-181	125	100	2.6
Single Engine No. 2	1,630-1,730	44- 48	1,320-1,440	27-31	153-175	125	100	2.7
Ground Idle	100	5	60	5	10	30	40	2.3

* 100% Main Rotor Torque = 3,000 hp (77,312 ft-lb at 203.8 rpm).
** 100% Tail Rotor Torque = 565 hp (979 ft-lb at 3,030 rpm).
*** 100% Drive Train Speed = 18,966 rpm Engine Drive Shaft, 203.8 rpm Main Rotor, 1,243 rpm Tail Rotor.

TABLE 12. TEST POWER SPECTRUM

Main Rotor Torque* (%)	Main Rotor Power (hp)	Tail Rotor Torque** (%)	Tail Rotor Power (hp)	Friction Losses and Accessory Power (hp)	Total Main Gearbox Input (hp)	Drive Train Speed*** (%)	Time (hr)	Test Condition
109	3,270	60	339	138	3,740	100	0.2	Dual Engine
102-105	3,060-3,150	52-60	294-339	137	3,480-3,600	100	1.2	Dual Engine
97-100	2,910-3,000	45-65	254-367	135-136	3,320-3,490	100	4.9	Dual Engine
93- 96	2,790-2,880	50-60	283-339	134	3,190-3,330	100	8.6	Dual Engine
87- 92	2,610-2,760	51-57	289-322	133-134	3,070-3,220	100	10.6	Dual Engine
80- 85	2,400-2,550	47-62	255-351	131-132	2,810-2,930	100	3.7	Dual Engine
66- 67	1,980-2,010	36-48	204-272	129	2,370-2,410	100	1.6	Dual Engine
60- 61	1,800-1,830	35-37	198-209	128	2,120-2,170	100	2.2	Dual Engine
50	1,500	30	170	126	1,800	100	0.2	Dual Engine
33- 38	990-1,140	17-18	96-104	122-123	1,210-1,370	100	1.5	Dual Engine
11	330	7	40	118	490	100	4.8	Dual Engine, Flat Pitch
5	60	5	10	30	100	40	4.8	Dual Engine, Ground Idle
62- 80	2,010-2,640	38-55	232-342	129-132	2,490-3,020	108-110	4.0	Dual Engine, Overspeed
60- 70	1,630-1,970	35-41	180-218	127-129	1,960-2,250	91- 94	4.0	Dual Engine, Underspeed
45- 48	1,350-1,440	28-32	159-181	125	1,640-1,750	100	2.6	Single Engine, No. 1
44- 48	1,320-1,440	27-31	153-175	125	1,630-1,730	100	2.7	Single Engine, No. 2

* 100% Main Rotor Torque = 3,000 hp (77,312 ft-lb at 203.8 rpm).
** 100% Tail Rotor Torque = 565 hp (979 ft-lb at 3,030 rpm).
*** 100% Drive Train Speed = 18,966 rpm Engine Drive Shaft, 203.8 rpm Main Rotor, 1,243 rpm Tail Rotor.

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TABLE 13. FUEL CONTROL/SPEED SELECTOR SENSITIVITY		
Condition (hp)	Fuel Consumption (lb/hr)	Fuel Control Shaft Position (deg)
No. 1 Engine		
483	400	78
720	490	81
1110	660	87
1508	810	90
1728	910	111
No. 2 Engine		
523	420	71
656	490	72.5
1079	670	77.5
1479	840	82.0
1671	920	83.0

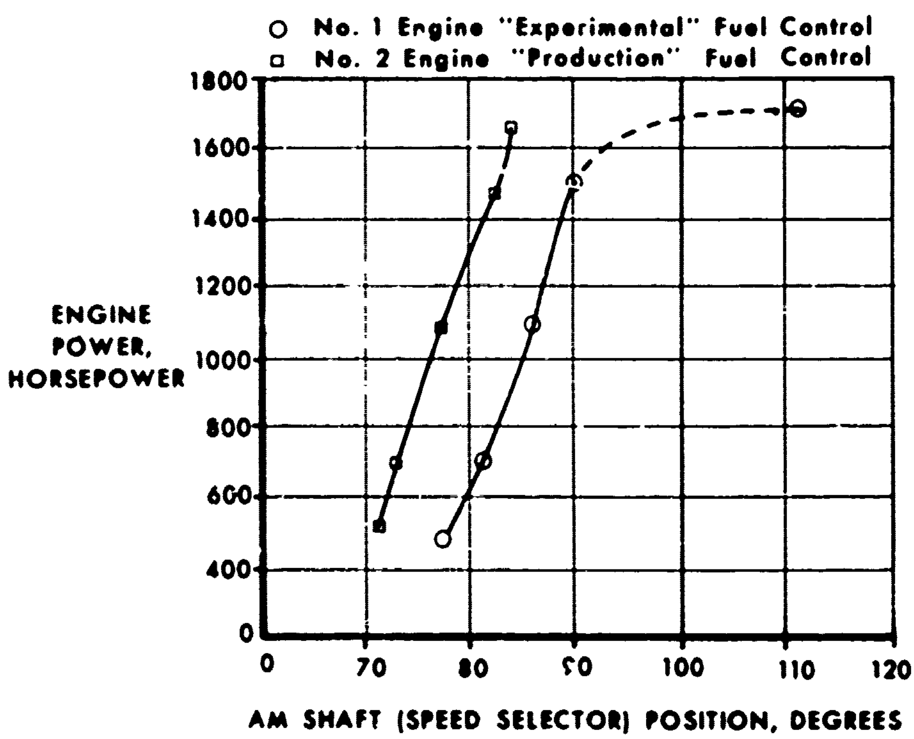

Figure 38. Fuel Control Speed Selector Sensitivity Graph

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ENGINE PERFORMANCE

Performance of the YT58-GE-16 engines was generally good during the test, although specified power levels could not be reached primarily due to hot-day performance loss and the absence of any power margin. Several minor engine-related operational and maintenance problems were ncountered and were resolved.

In view of earlier observations of fast-starting characteristics of these engines, the flow dividers were set on JP-4, while in fact JP-5 fuel was used during the test program. This procedure produced acceptable starting characteristics. Typical values of parameters measured during starts were: 21 to 24 percent starter Ng; between 3 and 10 seconds to light off; between 15 and 30 seconds to reach ground idle; maximum T5, 736°C Number 1 and 754°C Number 2; and starter dropout at 45-50 percent Ng. All are within limits. Typical operating data for both engines is shown for various powers in Table 14. These parameters remained within specified tolerance levels throughout the test program.

Performance Data

Standardized engine performance data for both engines is presented in Tables 15 and 16 and is plotted in Figures 39 through 42. This data is from single-engine runs on several days during the tiedown program and is corrected for local outside air temperature and barometric pressure. General Electric test cell data for these engines is also shown in the figures. Good agreement between test cell and tiedown data is obtained.

Temperature Data

Typical engine component temperature data, corrected to a 15°C standard day, is listed in Table 17 for various power levels, along with nominal limits and maximum observed temperatures. Since the engines were uncowled, all temperatures were well below limits.

TABLE 14. OPERATING DATA, YT58-GE-16 ENGINES.

Parameter	Test Condition: Ground Idle	Flat Pitch	60% NRP	80% NRP	90% NRP	100% NRP	Military Power	Over-Speed
No. 1 Fuel Flow (lb/hr)	130	325	660	830	830	840	890	750
No. 2 Fuel Flow (lb/hr)	150	330	650	890	890	900	930	860
No. 1 T_5 (°C)	650	510	690	769	778	785	814	743
No. 2 T_5 (°C)	650	500	670	765	770	785	814	777
No. 1 Gas Generator Speed (%)*	53.7	84.3	95.0	99.6	100.4	101.7	101.8	98.1
No. 2 Gas Generator Speed (%)*	54.7	84.5	94.8	99.4	100.1	100.4	102.2	99.7
No. 1 Free Turbine Speed (%)**	39	100.0	100.0	100.[illegible]	100.0	100.0	100.0	109.5
No. 2 Free Turbine Speed (%)**	39	100.0	100.0	100.0	100.0	100.0	100.0	109.5
Main Rotor Speed (%)***	39	100.0	100.0	100.0	100.0	100.0	100.0	109.5
No. 1 Engine Oil Temperature (°C)	78	68	72	70	[illegible]	78	80	78
No. 2 Engine Oil Temperature (°C)	85	65	81	75	[illegible]	82	38	85
No. 1 Engine Oil Pressure (psi)	16	40	50	56	[illegible]	55	57	56
No. 2 Engine Oil Pressure (psi)	18	41	48	54	5[illegible]	54	54	52
Main Gearbox Temperature (°C)	71	75	92	90	93	97	110	100
Main Gearbox Pressure (psi)	22	40	40	41	42	41	43	43

*100% Gas Generator Speed = 26,220 rpm
**100% Free Turbine Speed = 18,966 rpm
***100% Main Rotor Speed = 203.8 rpm

TABLE 15. YT58-GE-16 ENGINE STANDARDIZED PERFORMANCE DATA, NUMBER ONE ENGINE S/N 297004

Fuel Consumption, W_f (lb/hr)	Specific Fuel Consumption, W_f/SHP (lb/hr-hp)	Interturbine Temperature, T_5/θ ** (°R)	Gas Generator Speed, $N_g/\sqrt{\theta}$ ** (rpm)	Shaft Horsepower, SHP/$\delta\sqrt{\theta}$*** (hp)	Engine Drive Shaft Speed, N_f (rpm)
883	.522	1,868	26,271	1,668	18,985
895	.529	1,876	26,298	1,671	18,985
649	*	1,676	24,541	*	18,966
892	.544	1,838	26,401	1,632	19,061
881	*	1,850	26,117	*	18,947
695	*	1,701	24,732	*	18,966
666	*	1,715	24,732	*	18,947
861	*	1,838	26,013	*	18,985
852	.517	1,845	25,965	1,609	19,061
847	.514	1,843	25,940	1,610	19,080
926	.530	1,928	26,611	1,746	19,004
857	*	1,903	26,272	*	19,080
879	*	1,876	26,168	*	18,909
868	.505	1,809	26,143	1,673	19,061
777	*	1,796	25,500	*	18,985
384	.796	1,422	22,514	468	19,023
471	.654	1,498	23,256	698	19,042
636	.573	1,649	24,325	1,078	18,966
780	.517	1,787	25,401	1,464	18,947
877	.508	1,856	26,092	1,666	19,061
484	.690	1,519	23,421	710	19,042
639	.591	1,661	24,422	1,081	18,947
561	*	1,597	23,986	*	18,890
726	*	1,748	24,962	*	19,004

* Dual engine data, horsepower split unknown
** θ = (T + 273.16)/288.16, T = OAT in °C
*** δ = (Barometric pressure)/29.92, pressure in inches of mercury

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TABLE 16. YT58-GE-16 ENGINE STANDARDIZED PERFORMANCE DATA, NUMBER TWO ENGINE S/N 297006

Fuel Consumption, Wf (lb/hr)	Specific Fuel Consumption, Wf/SHP (lb/hr-hp)	Interturbine Temperature, $T5/\theta$ ** (°R)	Gas Generator Speed, $Ng/\sqrt{\theta}$ ** (rpm)	Shaft Horsepower, $SHP/\delta\sqrt{\theta}$ *** (hp)	Engine Drive Shaft Speed, Nf (rpm)
932	.551	1,885	26,375	1,668	18,909
935	.542	1,895	26,504	1,704	18,985
866	*	1,851	25,936	*	18,966
914	.553	1,887	26,323	1,640	19,535
895	.547	1,858	25,965	1,598	19,004
877	*	1,898	26,273	*	19,080
872	*	1,876	26,324	*	19,250
909	.530	1,869	26,323	1,688	18,890
919	.542	1,871	26,348	1,666	18,890
813	*	1,809	25,647	*	18,909
850	*	1,826	25,912	*	19,004
880	.539	1,864	26,194	1,589	19,137
777	*	1,608	25,680	*	18,985
405	.777	1,443	22,73[illegible]	508	19,042
474	.722	1,495	23,[illegible]	638	18,928
647	.600	1,657	24,475	1,049	18,966
812	.549	1,791	25,553	1,439	18,928
839	.532	1,857	26,14[illegible]	1,625	18,928
464	.761	1,487	23,344	594	19,042
639	.612	1,653	24,525	1,015	18,947
532	*	1,563	23,857	*	18,890
726	*	1,736	24,962	*	19,004

* Dual engine data, horsepower split unknown
** $\theta = (T + 273.16)/288.16$, T = OAT in °C
*** δ = (Barometric pressure)/29.92, pressure in inches of mercury

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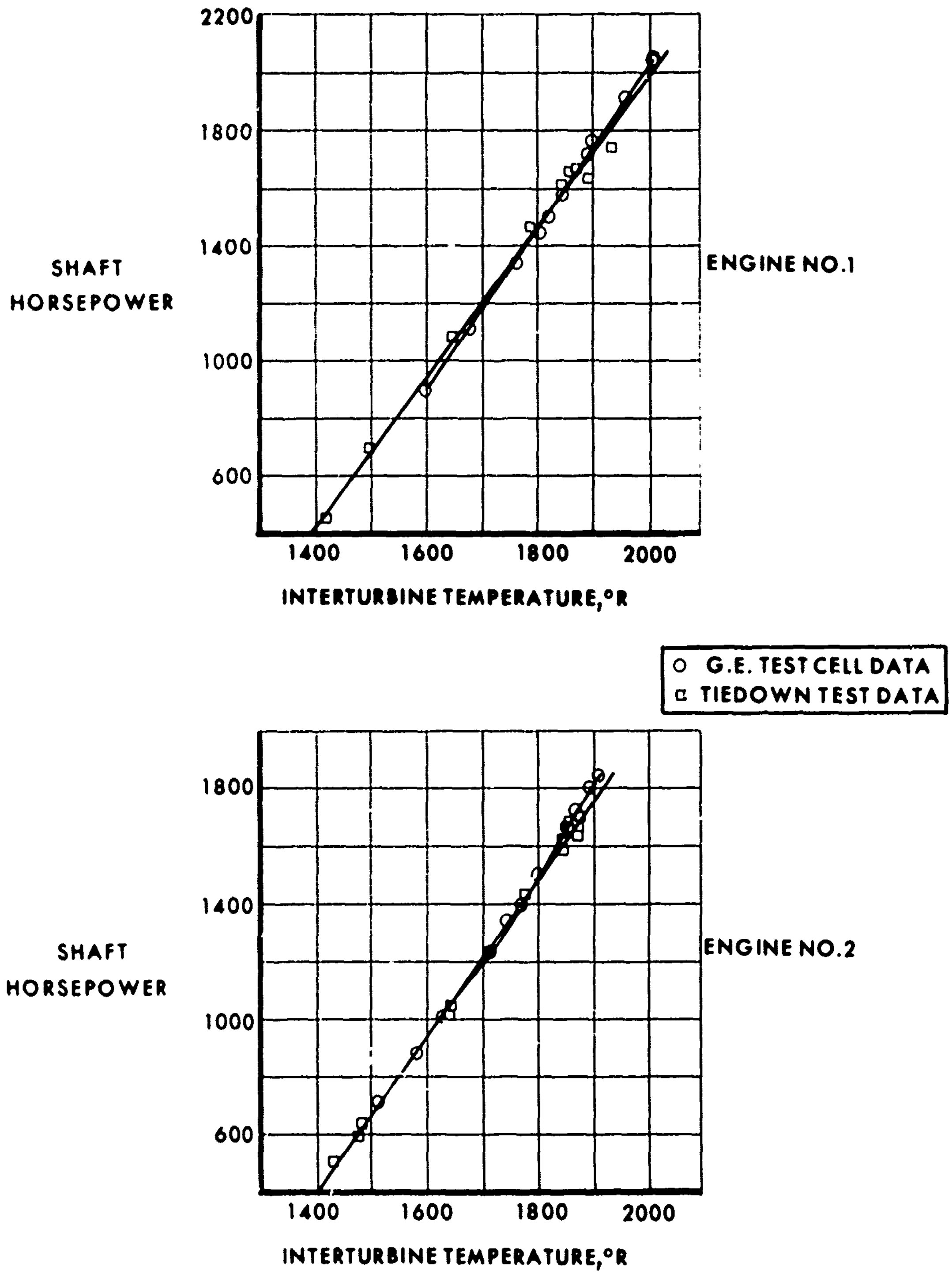

Figure 39. Power Versus Power Turbine Temperature

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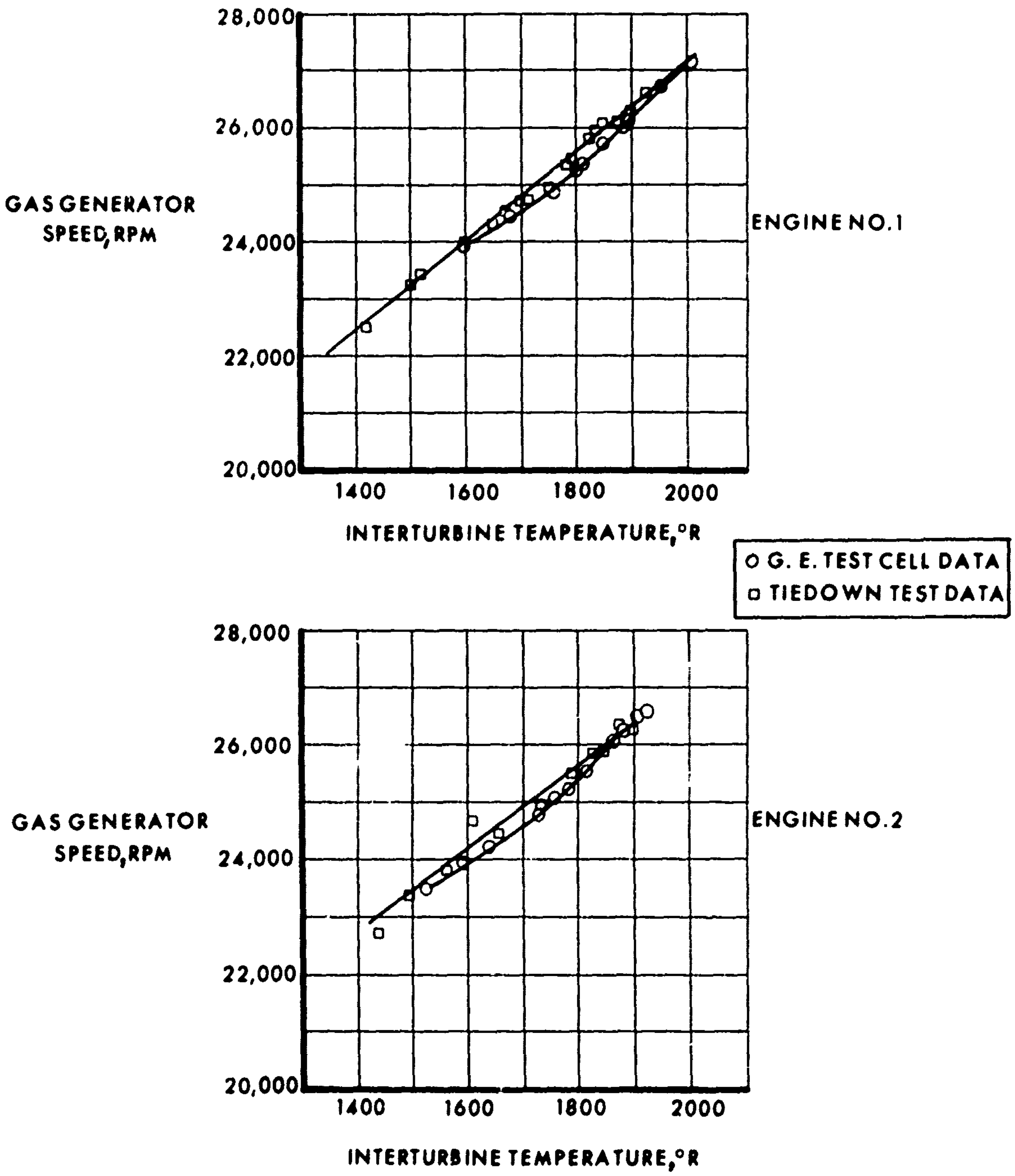

Figure 40. Gas Generator Speed Versus Power Turbine Temperature

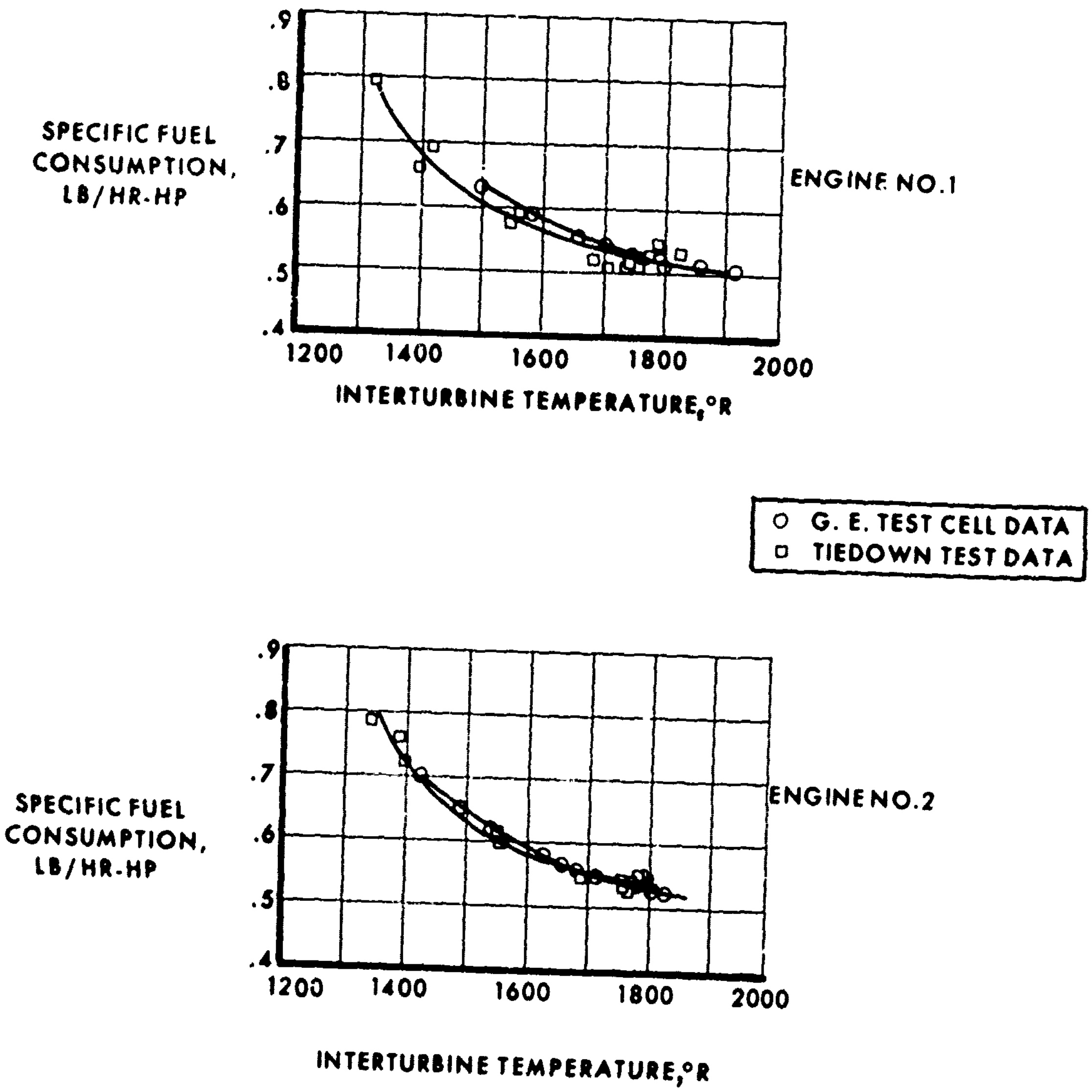

Figure 41. Specific Fuel Consumption Versus Power Turbine Temperature

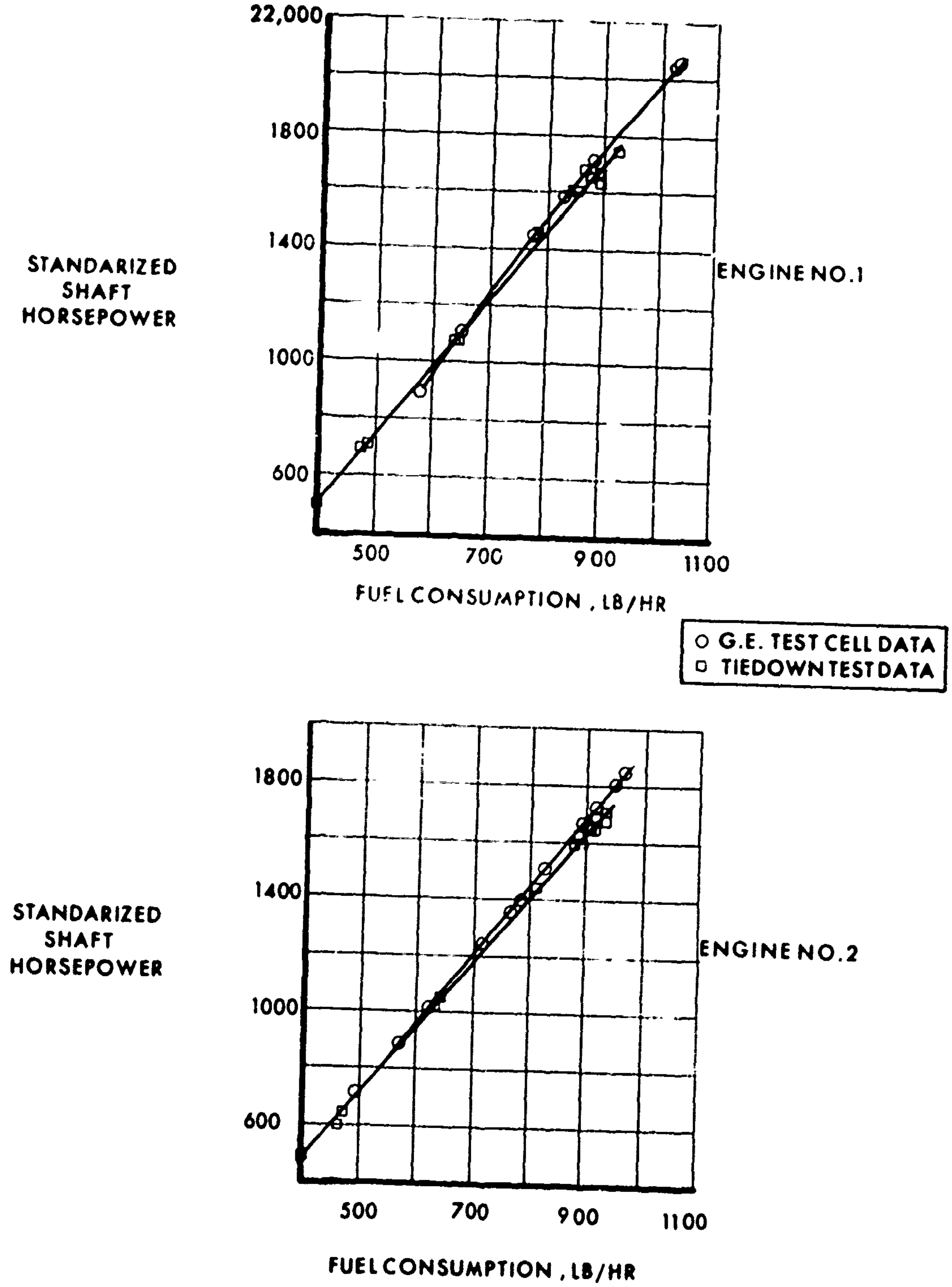

Figure 42. Shaft Horsepower Versus Fuel Consumption

TABLE 17. ENGINE COMPONENT TEMPERATURES

	Test Condition				
	Overspeed	NRP	Military Power	Maximum Recorded	G.E. Limits
No. 1 Engine					
Anti-ice Valve	58	49	58	77	204
Ignition Box	21	19	19	35	160
PMS Amplifier	67	54	63	79	120
Starting Bleed Valve	26	19	27	56	180
Flow Divider	55	54	62	76	132
Oil Cooler	67	49	54	66	149
Power Turbine Accessory Drive	84	89	89	100	163
High-Speed Shaft	16	15	15	28	316
T5 Harness	-	-	43	56	428
Fuel Pump	33	29	32	41	121
No. 2 Engine					
PMS Amplifier	46	39	49	68	121
Stator Vane Actuator	17	15	16	43	129
Combustor Casing	214	209	212	224	496
Stage 1 Turbine Casing	-	-	-	-	621
Stage 2 Turbine Casing	406	409	413	465	621
Compressor Casing, 12 o'clock	238	230	240	253	343
Compressor Casing, 3 o'clock	208	209	210	220	343
Compressor Casing, 6 o'clock	235	239	240	250	343
Compressor Casing, 9 o'clock	208	209	217	227	343
Exhaust Casing	392	389	391	465	621

Notes:
1. All table entries are temperatures in °C.
2. All values except "Maximum Recorded" and "G.E. Limits" are corrected to a 15°C standard day.
3. Maximum outside air temperature 33°C.

Vibration Data

The engine vibration pickups mounted at the General Electric specified locations (Figure 24) indicated that the amplitudes of vibration were within the manufacturer's required limits of 3 mils double amplitude in steady state and 5 mils double amplitude transient (2 seconds maximum). Of the six pickups on each engine, the highest in amplitude are shown in the graphs of Figure 43. The G. E. limits are also shown for the engine crotch location. Number 1 engine vibration levels were less than those of Number 2 engine.

The vibration pickups located on the engine torque tube are not engine pickups and are therefore not subject to the G. E. limits. Plots for these pickups are presented in the graphs of Figure 43, where some evidence of a resonance is seen at 90 percent rotor speed. No limits have been determined for these locations; however, the vibration levels observed there may have contributed to the gimbal mount deterioration.
Since these resonances are below normal operating speed and are not divergent, no safety problem is involved.

Oil Analysis/Consumption

The results of engine oil sample analysis are presented in Table 18. The threshhold limit criteria used are: Al-12 ppm, Fe-42 ppm, Cr-12 ppm. Any increase of 10 ppm between samples would warrant recommendations of investigation by the laboratory performing the analysis. These results show no damage or evidence of deterioration.

The oil consumption of these engines is listed in Table 19. The Number 2 engine developed an oil leak at 33.8 test hours which is responsible for the increase in consumption of that engine.

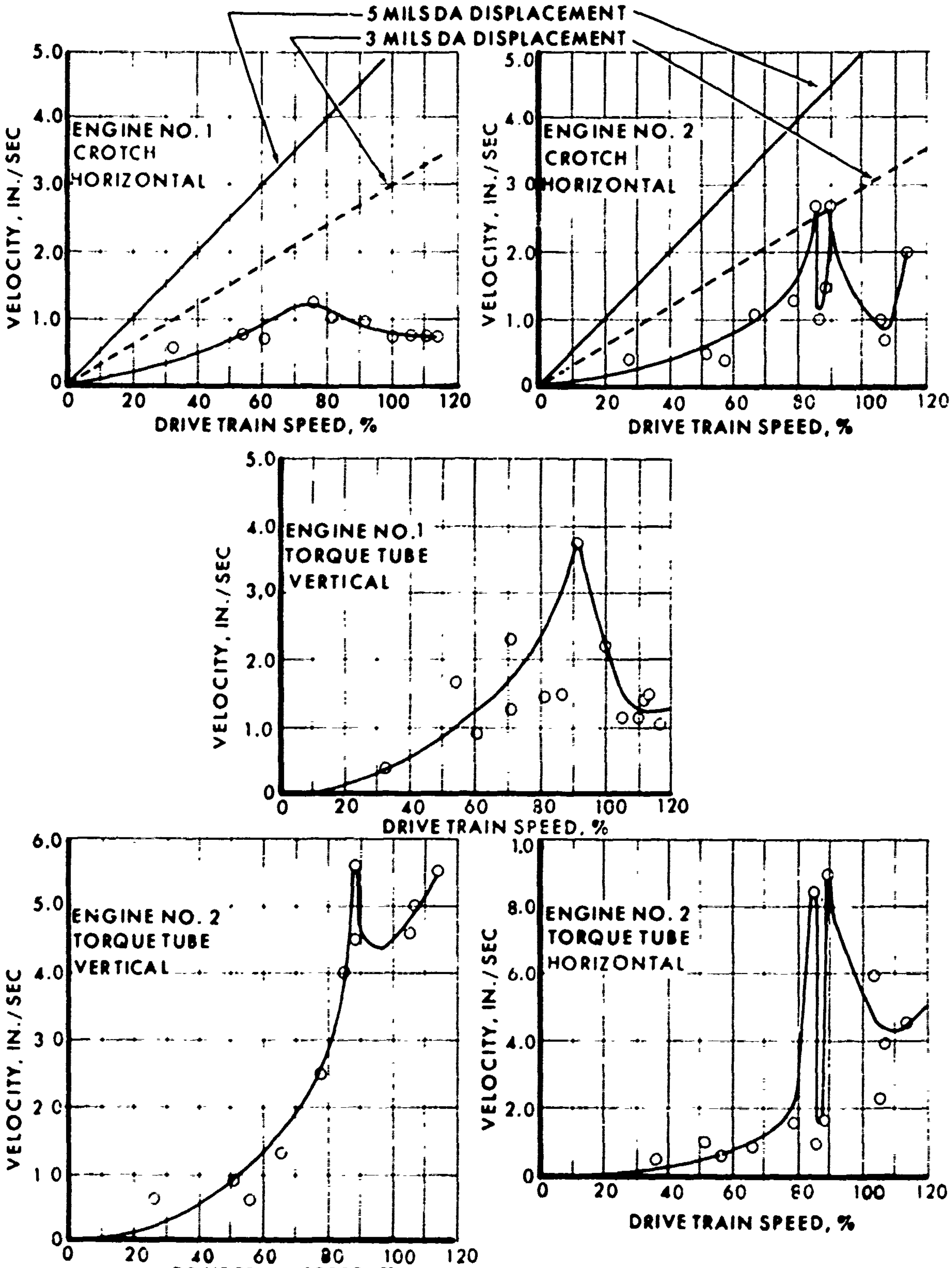

Figure 43. Engine Vibration Graphs

TABLE 18. ENGINE OIL SAMPLE ANALYSES										
Time (hr)	Al (ppm)	Fe (ppm)	Cr (ppm)	Ag (ppm)	Cu (ppm)	Sn (ppm)	Mg (ppm)	Ti (ppm)	Ni (ppm)	Si (ppm)
No. 1 Engine										
12.6	0	1	0	0	0	0	0	0	0	0
24.2	0	0	0	0	0	0	0	0	0	0
54.2	1	0	0	0	0	0	0	0	0	0
57.6	0	4	1	0	1	3	0	2	1	3
No. 2 Engine										
12.6	0	2	0	0	0	0	0	0	0	0
24.2	0	0	0	5	0	0	0	0	0	0
54.2	1	0	0	0	0	0	0	0	0	0
57.6	0	4	1	0	1	4	1	1	2	4

TABLE 19. ENGINE OIL CONSUMPTION DATA				
Test Time (hr)	Oil Added No. 1 Engine (cc)	Oil Added No. 2 Engine (cc)	Consumption Rate No. 1 Engine (cc/hr)	Consumption Rate No. 2 Engine (cc/hr)
35.5	-	-	234	246
39.6	600	600	146	146
43.7	590	1,130	144	276
47.6	540	1,050	138	269
52.6	860	1,080	172	216
57.6	1,170	1,990	234	[illegible]8

ROLLER GEAR TRANSMISSION PERFORMANCE

The roller gearbox main transmission performed very well during the tiedown test program. Fatigue cracks, though, were found in the second-row pinion rollers of the roller gear drive during the posttest teardown inspection. The gearbox ran cool, maintained good oil pressure and flow, and exhibited only minor operational problems. Manual effort required to turn the installed gearbox was considered high at the start of the test, but decreased to a relatively low level at the end of the 50-hour test. No evidence of metallic debris (beyond minor assembly debris) was detected in the gearbox chip detectors and filters throughout the test.

Test Data

At 2,000 main rotor horsepower, the measured cabin interior noise levels with the roller gear transmission were approximately the same as with a standard S-61 main gearbox when in hover flight. This comparison is illustrated in Figure 44. A full listing of noise levels of the roller gear transmission during tiedown tests at various power settings is given in Table 20.

TABLE 20. ACOUSTIC TEST RESULTS

Octave Band Center Frequency (cps)	Flat Pitch Noise Level (db)	1000 hp (Main Rotor) Noise Level (db)	2000 hp (Main Rotor) Noise Level (db)	3000 hp (Main Rotor) Noise Level (db)
Overall	111	114	115.5	118
31.5	89	93	96	97
63	97	100	102.5	109
125	103	105	108.5	109
250	104	104.5	107.5	109
500	106	107	111	116
1,000	105	106	103.5	105
2,000	102	100	110	108
4,000	101	104	104	105
8,000	102.5	103.5	104	105.5

Note: All measurements taken in aircraft cabin directly beneath roller gear transmission.

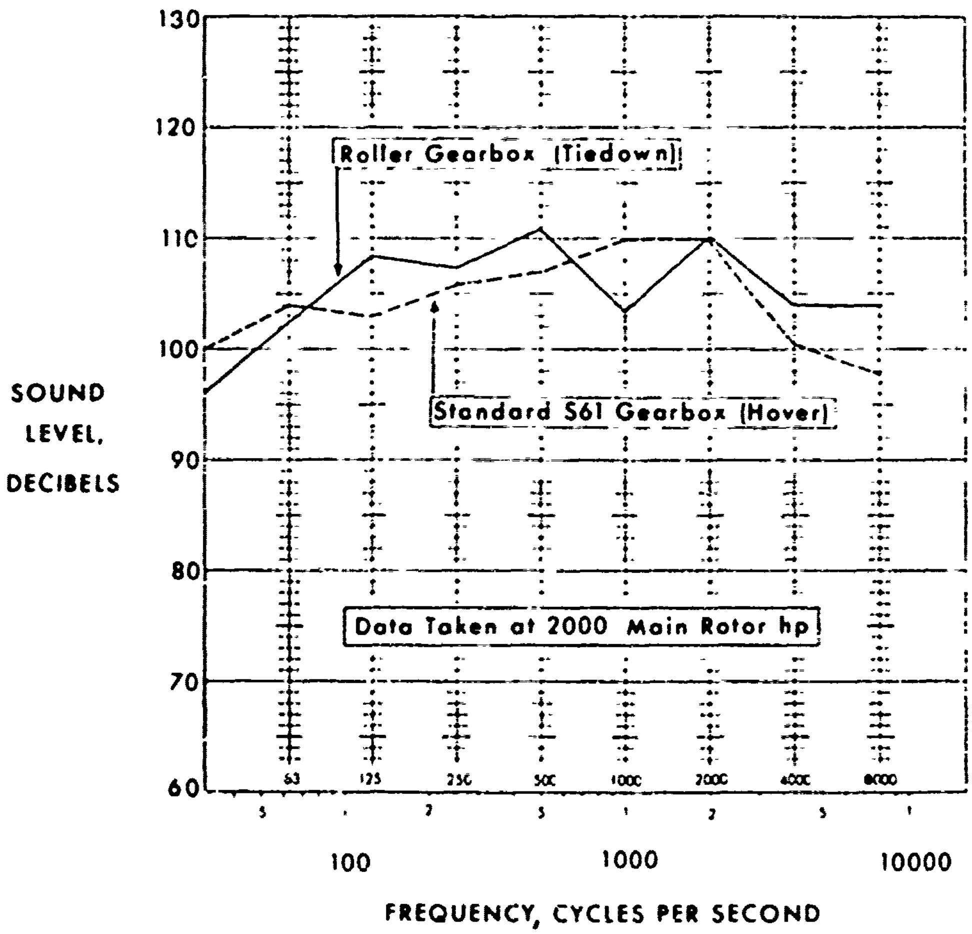

Figure 44. Noise Level, Roller Gear Transmission

Main gearbox lubrication system data at various power levels is presented in Table 21.

TABLE 21. OIL FLOW AND PRESSURE, ROLLER GEAR TRANSMISSION

Parameter	Minimum Recorded Value (100% NR)	Maximum Recorded Value (100% NR)	Ground Idle, (50% NR)
Lube Oil Flow (gpm)	22.8	24.4	16
Right Manifold (psi)	30	40	17
Main Manifold (psi)	34	41	20
Pump Outlet (psi)	68	80	42
Cooler Outlet (psi)	42	48	26
Left Manifold (psi)	34	39	18
Roller Drive Inlet (psi)	22	26	12

Main gearbox temperature data is presented in Table 22 in terms of typical temperatures at various power levels, corrected to a 15°C standard day. Maximum observed temperatures are also shown. The highest observed temperature was 121°C at the left input stack bearing on a 33°C day. Redline temperature had been established at 140°C. The mean temperatures recorded in the back-to-back transmission test stand, also shown in Table 22, compared well with the tiedown test gearbox and were exceeded only on hot days.

Vibration levels at the five main gearbox locations (shown in Figure 25) are included in the listing of Table 23. Each of these five locations showed a high-frequency vibration (3,500 cps or higher) due to gear clash and bearing frequencies from the roller gearbox. The lower frequencies observed can be attributed to drive shaft and rotor response characteristics.

TABLE 22. TRANSMISSION TEMPERATURES, ROLLER GEARBOX

Thermocouple Location	Test Condition					
	80% NRP	100% NRP	Over-Speed	Military Power	Maximum Recorded	Bench Test Mean Temp
Input Stack Bearing Left	89	104	82	101	121	115
Input Stack Bearing Right	92	106	83	103	119	115
Input Pinion Roller Bearing Left	-	-	-	-	-	110
Input Pinion Roller Bearing Right	-	-	-	95	114	110
Input Gear Roller Bearing Left	82	96	84	93	114	105
Input Gear Roller bearing Right	79	94	80	90	109	105
Input Gear Housing Left	87	103	90	99	120	115
Input Gear Housing Right	89	105	91	96	119	115
Freewheel Roller Bearing Left	73	87	75	84	103	100
Freewheel Roller Bearing Right	75	90	76	86	106	100
Main Rotor Shaft Roller Bearing	55	70	54	65	82	90
Outer Shaft Roller Bearing	71	86	72	81	101	98
Outer Shaft Housing	77	92	77	88	108	98
Tail Takeoff Housing Forward	76	90	76	87	107	100
Tail Takeoff Ball Bearing	51	66	50	75	109	80
Tail Takeoff Drive Roller	54	70	52	77	107	80
Main Rotor Ball Bearing	68	84	68	80	99	105
Roller Gear Post No. 1	56	72	54	80	103	100
Roller Gear Post No. 2	68	83	67	77	98	100
Roller Gear Post No. 3	58	75	55	78	95	100
Roller Gear Post No. 4	56	72	53	71	89	100
Roller Gear Post No. 5	61	76	58	76	95	100
Roller Gear Post No. 6	58	76	57	76	106	100
Roller Gear Post No. 7	59	75	55	75	97	100
Adaptor Housing Driver	39	41	27	42	61	70
Adaptor Housing Driven	38	54	37	55	69	70
Oil-Cooler In	70	86	69	80	102	95
Oil-Cooler Out	45	62	42	61	80	70

Notes:
1. All table entries are temperatures in °C.
2. All values except "Maximum Recorded" and "Test Stand Means" are corrected to a 15°C standard day.
3. Redline temperature is 140°C.
4. Maximum outside air temperature 33°C.

TABLE 23. VIBRATION SURVEY, ROLLER GEAR AIRCRAFT

Vibration Parameter	Maximum Level	Frequency (cps)	Maximum Level	Frequency (cps)	Maximum Level	Frequency (cps)	Test Condition
Main Gearbox Input Left	0.2-0.7 in./sec	3,500	0.2 in./sec	340	0.7 in./sec	19	Overspeed, Neutral Controls
Main Gearbox Input Right	0.2 in./sec	3,700	0.5 in./sec	340	0.8 in./sec	19	Overspeed, Neutral Controls
Main Gearbox Rear Cover Vertical	0.5 in./sec	5,000	1.0 in./sec	60	-	-	Overspeed, Neutral Controls
Main Gearbox Rear Cover Lateral	0.35 in./sec	6,900	0.5 in./sec	60	-	-	Overspeed, Neutral Controls
Main Gearbox Rear Cover Longitudinal	0.3 in./sec	4,300	0.7 in./sec	60	-	-	Overspeed, Neutral Controls
Cooler Shaft Vertical	0.2 in./sec	1,140	2.0 in./sec	17	-	-	100% NRP, Neutral Controls
Tail Bearing Vertical	0.2 in./sec	360	0.5 in./sec	55	0.4 in./sec	19	Overspeed, Neutral Controls
Intermediate Gearbox	2.5-3.0 g	550	2.5 g	54	-	-	100% NRP, Left Pedal
Tail Gearbox Input	1.0-4.5 g	300	1.0 g	20	-	-	100% NRP, Left Pedal
Tail Gearbox Output	0.8-2.0 g	600	0.7 g	22	-	-	Overspeed, Neutral Controls
Pilot Vertical	0.4-1.2 g	165	0.3 g	17	-	-	100% NRP, Forward Cyclic
Pilot Lateral	0.05 g	600	0.2-0.4 g	140	0.3 g	17	100% NRP, Forward Cyclic

Note:

When the measured vibration is composed of more than one frequency component, the amplitude and frequency of each component are listed.

Operational Problems

When the Number 2 engine was driving the main transmission at 100 percent rotor speed and the Number 1 engine speed was being accelerated for engagement, the freewheel unit was observed to fail to engage immediately and allowed the engine to overshoot by about 5 percent. The Number 2 freewheel unit also occasionally malfunctioned in this manner. The problem was first noted after 2.0 hours of test time. A temporary solution was to bring Number 1 up to 100 percent speed slowly, so that the freewheel unit engagement forces were low.

An improved main gearbox breather system was installed after 3.2 hours of test time to stop transmission oil leakage through the breather. This breather is the same as that used on the CH-53 accessory gearbox.

The main gearbox "Air Maze" filter was checked after 13.6 hours of test. After reinstallation, it began to leak due to distortion of the filter cover. A new cover was installed and the problem was eliminated. Figure 45 shows the location of this filter and the lube oil fitting which leaked oil at 29.5 test hours, when the fitting threads were found to be stripped due to too shallow engagement. The problem was solved by reworking the fitting to ensure deeper thread engagement. No further leakage occurred.

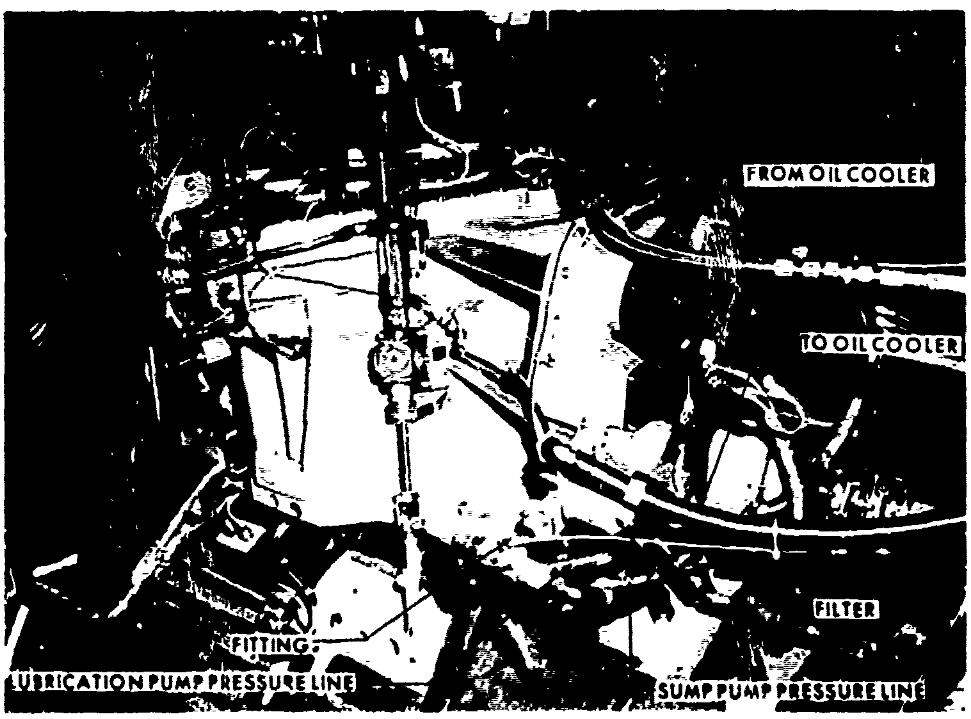

Figure 45. Lubrication Components, Roller Gear Transmission

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INSPECTION, ROLLER GEAR TRANSMISSION

After the 50-hour tiedown test was completed, a teardown inspection of the roller gear transmission was conducted. The visual and non-destructive testing results are presented in Table 24 for the roller gear unit components and in Table 25 for the remaining gearbox components, excluding the roller gear transmission. The results are summarized below.

Visual inspection of the roller gear components revealed slight surface distress on the lower small-diameter rollers of first-row pinions serial numbers 55 and 56 (Figure 46). As seen from Figure 47, which shows the assembled location of the roller gear components, the identity of the bearings and post within the second-row gear and the appropriate thermocouple (T number), the second-row gear, serial number 60, mated with these pinions. The second-row gear rollers showed only faint markings due to the rolling action with these pinions. Examination of the first-row pinion distressed area revealed a frosted surface approximately 0.12 inch wide around the circumference. This area started on the roller surface where the crown relief of the second-row roller commenced.

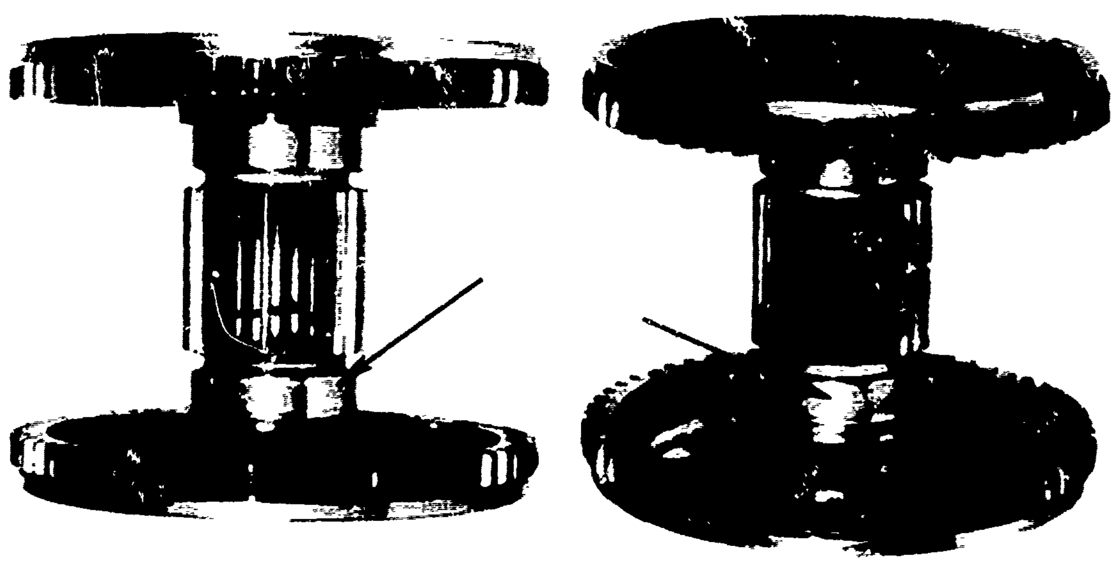
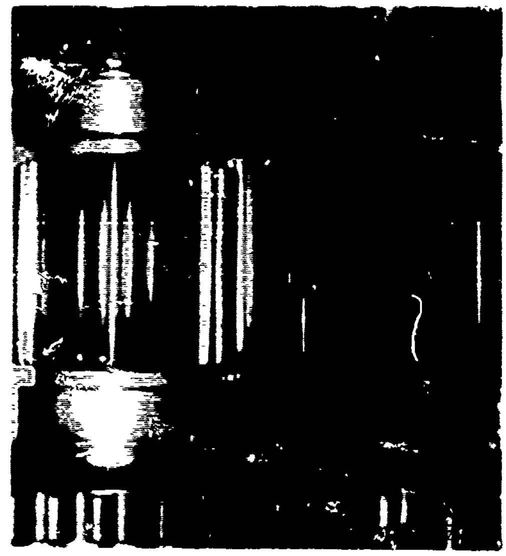


Figure 46. Frosted Roller Surface, First-Row Pinion

As a result of insufficient blending of the first-row pinion roller radius serial number 69, the sun gear exhibited a hard line close to the shoulder radius on the upper roller. Apart from these surfaces, all other roller surfaces were in excellent condition. The second-row gear rollers still retained the Dulite (black oxide) coating that was applied for corrosion protection.

The gear teeth on all the roller gear components showed excellent contact patterns with only negligible signs of wear.

VIEW ON ARROW



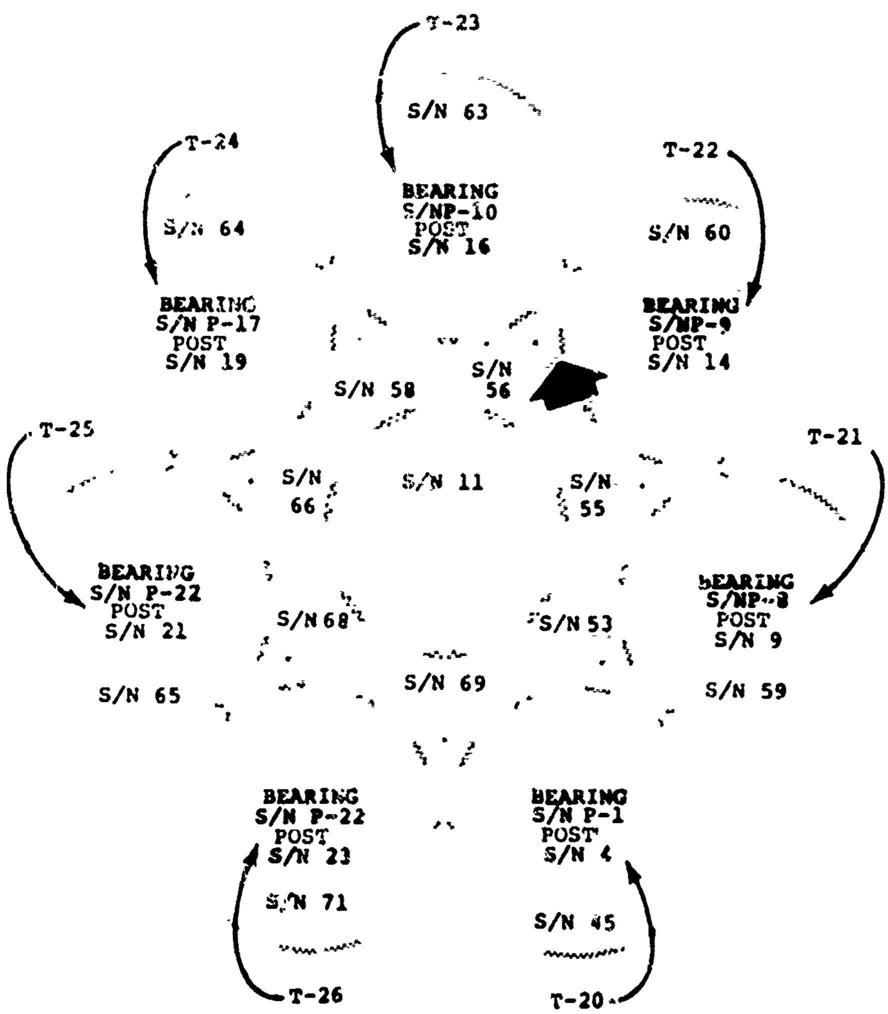


Figure 47. Roller Gear Assembly

The second-row gear assemblies all exhibited slight fretting corrosion between the outer race of the spherical roller bearing and the gear bore. Figure 48 shows the extent of this fretting. Experience has shown that this type of fretting corrosion is not detrimental. Figure 48 also shows the slight fretting corrosion around the holes through which the taper lock bolts fastened the gear/flange assembly to the second-row gear. This corrosion was caused by flexure of the gear/flange assembly induced by the ring gear mesh forces. This same flexure caused wear of the spacer (shown in Figure 48) which was used to provide axial clamp-up of the outer race of the bearing.

Both left and right input bevel pinions showed slight tip interference from mating gears. Figure 49 shows the hard line resulting from this interference. The gear tooth bearing pattern is barely discernible in the picture, but is identical to the desired pattern. Visual inspection of the mating bevel gear revealed a line along the tip of the drive side of the gear teeth. The edge break along this tip was 0.004 inch. This was insufficient and resulted in the line on the input pinion. Also visible in Figure 49 is slight fretting between the roller bearing and the pinion shaft. This was not considered to be detrimental to shaft or bearing operation.

The left-hand freewheel unit had a tendency to engage late (i.e., overshoot). Inspection of this unit showed all the components to be in satisfactory condition; however, eight of the fourteen rollers exhibited wear marks from chucking in the cage pockets. Corresponding wear marks were visible in the cage pockets. Dimensional inspection of the rollers showed them all to be within ± 0.0001 inch, and similar inspection of the cam and housing revealed them to be within drawing tolerance. Comparison with the right-hand freewheel unit revealed no differences except for the wear bands on the left-hand rollers. During the 200-hour endurance test, chucking on both left- and right-hand freewheel units occurred. Stronger springs were installed for the 50-hour tiedown test, increasing the force on the cage from 2.1 lb to 2.6 lb when in the driving mode. This markedly decreased the degree of chucking on both units. Future tests will be conducted using springs which will provide an increased force on the cage of 3.1 lb when in the driving mode.

Apart from slight fretting oxidation on free-floating quill shaft splines, the remaining transmission dynamic components were in excellent condition. Gear teeth contact patterns on the accessory gears and adaptor box gears were excellent.

Figure 48. Fretting, Second-Row Gear Assembly

Figure 49. Wear Pattern, Input Bevel Pinion

TABLE 24. ROLLER GEAR UNIT INSPECTION: 50-HOUR TIEDOWN TEST (Sheet 1)

Part Number	Nomenclature	Serial No.	Visual Inspection	Ultrasonic, Magnaglow, or Zyglow Inspection*	Comments
RG351-11183-041	Sun Gear	11	Gear tooth excellent - Hard line on upper roller shoulder	No indications	Wear mark caused by insufficient crown blending by first-row pinion S/N 69
RG351-11182-062	1st row pinion	53	Rollers and gear teeth excellent	No indications	-
RG351-11182-062	1st row pinion	56	Lower inside roller exhibits 1/8-inch-wide wear path - gear teeth excellent	No indications	Frosting of roller surface
RG351-11182-062	1st row pinion	56	Lower inside roller exhibits 1/8-inch-wide wear path - gear teeth excellent	No indications	Frosting of roller surface
RG351-11182-062	1st row pinion	58	Rollers and gear teeth excellent	No indications	-
RG351-11182-062	1st row pinion	66	Burnish marks on inner rollers - gear teeth excellent	No indications	-
RG351-11182-062	1st row pinion	68	Rollers and gear teeth excellent - upper roller surface is not polished	No indications	-
RG351-11182-062	1st row pinion	69	Hard line on upper roller gear teeth excellent	No indications	Insufficient crown blend with edge radius
RG351-11181-062	2nd row pinion	45	Rollers and gear teeth excellent	Crack indication at lower roller weld*	Crack originating from EB weld
RG351-11181-062	2nd row pinion	59	Rollers and gear teeth excellent	Crack indication at lower roller weld*	Crack originating from EB weld
RG351-11181-062	2nd row pinion	60	Rollers and gear teeth excellent	Crack indication at lower roller weld*	Crack originating from EB weld
RG351-11181-062	2nd row pinion	63	Rollers and gear teeth excellent	Crack indication at lower roller weld*	Crack originating from EB weld
RG351-11181-062	2nd row pinion	64	Rollers and gear teeth excellent	No indications*	-

TABLE 24. ROLLER GEAR UNIT INSPECTION: 50-HOUR TIEDOWN TEST (Sheet 2)

Part Number	Nomenclature	Serial No.	Visual Inspection	Ultrasonic, Magnaglow, or Zyglow Inspection*	Comments
RG351-11181-062	2nd row pinion	65	Rollers and gear teeth excellent	Crack indications at lower roller weld*	Crack originating from EB weld
RG351-11181-062	2nd row pinion	71	Rollers and gear teeth excellent	Crack indications at lower roller weld*	Crack originating from EB weld
RG351-11185-103	Hub	03	Excellent	No indications	-
RG351-11185-041	Plate assy	07	Excellent	No indications	-
RG351-11176-041	Plate assy	04	Excellent	No indications	-
RG351-11187-101	Splined plate	04	7 teeth located symmetrically exhibit full face loading	No indications	Reaction torque deflections - no wear
RG351-11173-101	Nut	-	Excellent	No indications	-
RG351-11173-101	Nut	-	Excellent	No indications	-
RG351-11173-101	Nut	-	Excellent	No indications	-
RG351-11173-101	Nut	-	Excellent	No indications	-
RG351-11173-101	Nut	-	Excellent	No indications	-
RG351-11173-101	Nut	-	Excellent	No indications	-
RG351-11173-101	Nut	-	Excellent	No indications	-
RG351-11139-101	Oil pump gear	01	Gear pattern excellent	No indications	-
RG351-11186-041	Plate assy	[illegible]	Excellent	No indications	-
RG351-11177-101	Post	[illegible]	Excellent	No indications	-
RG351-11177-101	Post	09	Excellent	No indications	-
RG351-11177-101	Post	[illegible]	Excellent	No indications	-
RG351-11177-101	Post	[illegible]	Excellent	No indications	-
RG351-11177-101	Post	19	Excellent	No indications	-

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TABLE 24. ROLLER GEAR UNIT INSPECTION: 50-HOUR TIEDOWN TEST (Sheet 3)

Part Number	Nomenclature	Serial No.	Visual Inspection*	Ultrasonic, Magnaglow, or Zyglow Inspection	Comments
RG351-11177-101	Post	21	Excellent	No indications	-
RG351-11177-101	Post	23	Excellent	No indications	-
RG351-11184-041	Ring gear	06	Gear teeth excellent	No indications	Excellent gear patterns
22313 VAG	Spherical Brg	P1	Excellent	-	-
22313 VAG	Spherical Brg	P8	Excellent	-	-
22313 VAG	Spherical Brg	P9	Excellent	-	-
22313 VAG	Spherical Brg	P10	Excellent	-	-
22313 VAG	Spherical Brg	P17	Excellent	-	-
22313 VAG	Spherical Brg	P22	Excellent	-	-
22313 VAG	Spherical Brg	P23	Excellent	-	-
RG351-11179-101	Spacer	-	Face worn .001 - .003	No indications	Wear due to working of 2nd row gear/flange assy
RG351-11179-101	Spacer	-	Face worn .001 - .003	No indications	Wear due to working of 2nd row gear/flange assy
RG351-11179-101	Spacer	-	Face worn .001 - .003	No indications	Wear due to working of 2nd row gear/flange assy
RG351-11179-101	Spacer	-	Face worn .001 - .003	No indications	Wear due to working of 2nd row gear/flange assy
RG351-11179-101	Spacer	-	Face worn .001 - .003	No indications	Wear due to working of 2nd row gear/flange assy
RG351-11179-101	Spacer	-	Face worn .001 - .003	No indications	Wear due to working of 2nd row gear/flange assy
RG351-11179-101	Spacer	-	Face worn .001 - .003	No indications	Wear due to working of 2nd row gear flange assy

* Indicates crack found by Ultrasonic Inspection.

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TABLE 25. ROLLER GEARBOX INSPECTION (EXCLUDING ROLLER GEAR COMPONENTS)
50-HOUR TIEDOWN TEST (Sheet 1)

Part Number	Nomenclature	S/N	Visual Inspection	Magnaglow or Zyglow Inspection	Comments
RG351-11113-101	Input bevel RH	09	Hard line in teeth root - Slight fretting between roller bearing and pinion	No indications	Hard line caused by insufficient teeth edge chamfer on driven gear
MM212VM9-SMBR-A 1584	Stack brgs RH	109	Excellent	-	-
SB2154-1	Roller brg RH	115	Excellent	-	-
RG351-11117-102	Nut RH	-	Excellent	No indications	-
RG351-11117-101	Nut RH	-	Excellent	No indications	-
RG351-11113-101	Input bevel LH	01	Hard line in teeth root - Slight fretting between roller bearing and pinion	No indications	Hard line caused by insufficient teeth edge chamfer on driven gear
MM212VM9-SMBR-A1584	Stack brgs LH	106	Excellent	-	-
SB2154-1	Roller brg LH	111	Excellent	-	-
RG351-11117-102	Nut LH	-	Excellent	No indications	-
RG351-11117-101	Nut LH	-	Excellent	No indications	-
RG351-11117-103	Nut LH	-	Excellent	No indications	-
111-KS-400	Bearing RH	-	Excellent	-	-
NAS 1493-14	Nut RH	-	Excellent	No indications	-
RG351-11146-101	Quill shaft RH	09	Int & ext splines show slight fretting	No indications	Requires improved lubrication
RG351-11139-102	Bushing RH	-	Excellent	-	-
1838-JD-400-B	Ball brg	E22	Excellent	-	-
RG351-11109-102	Nut RH	-	Excellent	No indications	-
RG351-11136-101	Pin (2 pcs) RH	-	Excellent	-	-

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TABLE 25. ROLLER GEARBOX INSPECTION (EXCLUDING ROLLER GEAR COMPONENTS) 50-HOUR TIEDOWN TEST (Sheet 2)

Part Number	Nomenclature	Serial No.	Visual Inspection	Magnaglow or Zyglow Inspection	Comments
RG351-11135-101	Cage RH	10	Excellent	No indications	-
RG351-11133-041	Cam RH	06	Excellent	No indications	Excellent load pattern
RG351-11117-104	Nut RH	-	Excellent	No indications	-
SB2157-2	Roller brg RH	466	Excellent	-	-
RG351-11131-101	Spur shaft RH	12	Slight fretting about holes in mounting	No indications	Common occurrence
RG351-11132-101	Spur gear RH	09	Slight fretting about mounting holes in flange	No indications	Common occurrence
RG351-11139-101	Bushing RH	-	Excellent	-	-
X3762	Roller RH (14 pcs)	-	Excellent	No indications	-
RG351-11128-101	Bevel gear RH	09	Hard line on teeth edge	No indications	Insufficient chamfers on edge of gear teeth
RG351-11129-101	Bevel shaft RH	10	Excellent	No indications	-
SB 1056-2	Duplex ball brg RH	1836	Excellent	-	-
RG351-11134-101	n housing RH	88	Slight fretting on ext spline	No indications	Requires improved lubrication
RG351-11143-101	Nut RH	-	Excellent	No indications	-
MR-1922-C-400	Roller brg RH	E16	Excellent	-	-
RG351-11126-041	Housing RH	003	Excellent	-	-
RG351-11109-101	Nut RH	-	Excellent	No indications	-
RG351-11117-103	Nut RH	-	Excellent	No indications	-
111-KS-400	Bearing LH	-	Excellent	-	-
NAS 1493-14	Nut LH	-	Excellent	No indications	-

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TABLE 25. ROLLER GEARBOX INSPECTION (EXCLUDING ROLLER GEAR COMPONENTS) 50-HOUR TIEDOWN TEST (Sheet 3)

Part Number	Nomenclature	Serial No.	Visual Inspection	Magnaglow or Zyglow Inspection	Comments
RG351-11146-101	Quill shaft LH	03	Ext & int spline slight fretting	No indications	Requires improved lubrication
RG351-11139-101	Bushing LH	-	Excellent	-	-
1838-JD-400-B	Ball brg LH	E9	Excellent	-	-
RG351-11109-102	Nut LH	-	Excellent	No indications	-
RG351-11136-101	Pin (2 pcs) LH	-	Excellent	-	-
RG351-11135-101	Cage LH	07	Wear marks in corner pockets	No indications	Rollers chucking
RG351-11133-041	Cam LH	05	Excellent	No indications	Excellent load pattern
RG351-11117-104	Nut LH	-	Excellent	No indications	-
RG351-11117-104	Nut LH	-	Excellent	No indications	-
SB2157-2	Roller brg LH	443	Excellent	-	-
RG351-11131-101	Spur shaft LH	-	Excellent	No indications	-
RG351-11132-101	Spur gear LH	01	Excellent	No indications	-
RG351-11139-101	Bushing LH	-	Excellent	-	-
X3762	Roller (14 pcs) LH	-	All rollers exhibit wear bands	No indications	Rollers chucking
RG351-11128-101	Bevel gear LH	05	Hard line on teeth edge	No indications	Insufficient chamfer on edge of teeth
RG351-11129-101	Bevel shaft LH	04	Slight fretting on internal spline	No indications	Insufficient lubrication
SB1056-2	Duplex brg LH	1832	Excellent	-	-
RG351-11134-101	Cam hsg LH	86	Excellent	No indications	-

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TABLE 25. ROLLER GEARBOX INSPECTION (EXCLUDING ROLLER GEAR COMPONENTS)
50-HOUR TIEDOWN TEST (Sheet 4)

Part Number	Nomenclature	Serial No.	Visual Inspection	Magnaglow or Zyglow Inspection	Comments
RG351-11143-101	Nut LH	-	Excellent	No indications	-
MR-1922-C-400	Roller brg LH	E4	Excellent	-	-
RG351-1[illegible]26-041	Housing LH	02	Excellent	No indications	-
RG351-11109-101	Nut LH	-	Excellent	No indications	-
RG351-11193-101	Bevel gear	5	Excellent	No indications	Excellent gear pattern
34306 34478	Timken brg Timken brg	-	Excellent	-	-
RG351-11266-041	Oil tube	-	Excellent	-	-
RG351-11191-041	Housing	02	Excellent	No indications	-
SB3253A-1 SB3253B-1	Timken brg Timken brg	-	Excellent	-	-
RG351-11117-105	Nut	-	Excellent	No indications	-
RG351-11248-101	Spacer	-	Excellent	No indications	-
RG351-11157-101	Quill shaft	02	Slight fretting on both external splines	No indications	Insufficient lubrication
RG351-11156-102	Clip	-	Excellent	No indications	-
RG351-11178-101	Nut	-	Excellent	No indications	-
RG351-11151-041	Hsg assy	05	Excellent	No indications	-
RG351-11155-101	Bevel gear	02	Excellent	No indications	Excellent gear pattern
SB3602B-1 SB3602A-1	Timken brg LL639210	-	Excellent	-	-
RG351-11137-101	Spacer	-	-	No indications	-
RG351-11153-101	Outer shaft	04	Internal spline shows slight fretting	No indications	Requires more lubrication

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TABLE 25. ROLLER GEARBOX INSPECTION (EXCLUDING ROLLER GEAR COMPONENTS) 50-HOUR TIEDOWN TEST (Sheet 5)

Part Number	Nomenclature	Serial No.	Visual Inspection	Magnaglow or Zyglow Inspection	Comments
MR-1340-C-400	Roller brg	12	Excellent	-	-
RG351-11109-103	Nut	-	Excellent	No indications	-
RG351-11212-101	Spur gear	02	Excellent	No indications	-
SB2102-1	Roller brg	3306	Excellent	-	-
SB1106-1	Ball brg	-	Excellent	-	-
B-107716	Seal	-	Excellent	-	-
S6135-20053-3	Nut	-	Excellent	No indications	-
RG351-11211-101	Spur gear	05	Excellent	No indications	-
SB2102-1	Roller brg	3338	Excellent	-	-
SB1106-1	Ball brg	-	Excellent	-	-
B-107716	Seal	-	Excellent	-	-
S6135-20053-3	Nut	-	Excellent	No indications	-
RG351-11223-101	Gear shaft	06	Excellent	No indications	-
SB2100-2	Roller brg	206	Excellent	-	-
RG351-11222-101	Gear	06	Excellent	No indications	-
RG351-11197-101	Gear	07	Excellent	No indications	-
NAS 1493-12	Nut	-	Excellent	No indications	-
SB1157-1	Ball brg	-	Excellent	-	-
NAS 1493-13	Nut	-	Excellent	No indications	-
RG351-11196-101	Gear	04	Excellent	No indications	-
RG351-11209-101	Gear	03	Excellent	No indications	-
HU1013EA35612	Roller brg	5	Excellent	-	-

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TABLE 25. ROLLER GEARBOX INSPECTION (EXCLUDING ROLLER GEAR COMPONENTS) 50-HOUR TIEDOWN TEST (Sheet 6)

Part Number	Nomenclature	Serial No.	Visual Inspection	Magnaglow or Zyglow Inspection	Comments
SB2102-1	Roller brg	3342	Excellent	-	-
SB1105-1	Ball brg	131	Excellent	-	-
CB66-4	Seal	-	Excellent	-	-
S6135-20053-2	Nut	-	Excellent	No indications	-
S6135-20181-2	Gear	723	Excellent	No indications	-
SB2102-1	Roller brg	3347	Excellent	-	-
SB1105-1	Ball brg	-	Excellent	-	-
CB66-4	Seal	-	Excellent	-	-
S6135-20053-2	Nut	-	Excellent	No indications	-
RG351-11233-101	Oil pump	1171	Slight fretting on internal square drive	-	Insufficient lubrication
RG351-11218-041	Elbow assy	003	Excellent	-	-
S6135-20053-	Nut	-	Excellent	No indications	-
SB1104-3	Ball brg	-	Excellent	-	-
RG351-11216-101	Spacer	14	Excellent	No indications	-
SB2102-1	Roller brg	3338	Excellent	-	-
RG351-11214-101	Gear	05	Excellent	No indications	-
RG351-11215-101	Quill shaft	74	Slight fretting on external square drive	No indications	Insufficient lubrication
NAS1493-12	Nut	-	Excellent	No indications	-
M211KMBRA1590	Ball brg	-	Excellent	-	-
RG351-11255-101	Gear	05	Excellent	No indications	-

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TABLE 25. ROLLER GEARBOX INSPECTION (EXCLUDING ROLLER GEAR COMPONENTS) 50-HOUR TIEDOWN TEST (Sheet 7)

Part Number	Nomenclature	Serial No.	Visual Inspection	Magnaglow or Zyglow Inspection	Comments
SB1159-1	Ball brg	-	Excellent	-	-
NAS1493-10	Nut	-	Excellent	No indications	-
NAS1493-12	Nut	-	Excellent	No indications	-
M211KMBRA1590	Ball brg	-	Excellent	-	-
NAS1493-12	Nut	-	Excellent	No indications	-
NAS1493-10	Nut	-	Excellent	No indications	-
SB1159-1	Ball brg	-	Excellent	-	-
RG351-11257-101	Gear	02	External spline shows slight wear pattern	No indications	Normal wear
HU-1012-LAR-3514	Roller brg	6	Excellent	-	-
CB81-23	Seal	-	Excellent	-	-
S6137-23067-1	Flange	-	Excellent	No indications	-
S6137-23047-3	Nut	-	Excellent	No indications	-
RG351-11270-041	Coupling	-	Excellent	No indications	-
RG351-11270-041	Coupling	-	Excellent	No indications	-
RG351-11160-042	Main rotor shaft	04	Excellent	No indications	-
525519	Seal	-	-	-	-
R1838-C-400	Roller brg	E9	-	-	-
RG351-11154-101	Spur gear	03	Excellent	No indications	-
CB63-4	Seal	-	-	-	-
SB1357-2	Ball brg	-	-	-	-

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TABLE 25. ROLLER GEARBOX INSPECTION (EXCLUDING ROLLER GEAR COMPONENTS) 50-HOUR TIEDOWN TEST (Sheet 8)

Part Number	Nomenclature	Serial No.	Visual Inspection	Magnaglow or Zyglow Inspection	Comments
RG351-11194-101	Quill shaft	04	Slight fretting at both ends	No indications	More lubricant required
RG351-11205-101	Quill shaft	02	Fretting on large external spline	No indications	Insufficient lubrication
S6135-20713-1	Nut	-	Excellent	No indications	-
S6135-20713-1	Nut	-	Excellent	No indications	-
RG351-11256-101	Gear	02	Excellent	No indications	-
H211KMBRA1590	Bearing (3)	-	Excellent	-	-
SB1159-1	Bearing	-	Excellent	-	-
RG351-11251-041	Housing assy	03	Excellent	No indications	-
RG351-11253-041	Cover assy	03	Excellent	No indications	-
RG351-11102-041	Main hsg	04	Excellent	-	-
SB2154-1	Bearing	111	Excellent	-	-
SB2154-1	Bearing	115	Excellent	-	-
MR1922C400	Bearing	E4	Excellent	-	-
MR1922C400	Bearing	E16	Excellent	-	-
SB2100-2	Bearing	206	Excellent	-	-
RG351-11104-041	Top cover assy	05	Excellent	-	-
RG351-11158-041	Guide assy	03	Excellent	-	-
RG351-11186-041	Plate assy	04	Excellent	No indications	-
SB1357-2	Duplex brg	428	Excellent	-	-
RG351-11119-041	Pump assy	B606	Excellent	-	-

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Ultrasonic Inspection, Roller Gear Components

The electron beam welds of the roller gear drive components were inspected by the pulse-echo ultrasonic inspection technique. Inspection was conducted in accordance with an ultrasonic inspection procedure developed by Sikorsky Aircraft specifically for the roller gear electron-beam-welded components.

Prior to the start of the 50-hour tiedown test, ultrasonic inspection was performed on the electron beam welds of the roller gear components, and facsimile recordings C-scans were obtained. At the completion of the 50-hour test, this inspection was repeated, and the C-scans were compared to determine if any degradation had accrued in the weld. It was found that none had occurred in the welds in the sun gear and the first-row pinion welds; however, the outer roller welds in the second-row gears, identified in Figure 50, did show indications of crack propagation at the root of the weld. Figures 51 and 52 show the ultrasonic inspection methods whereby the degradation of the welds was discovered.

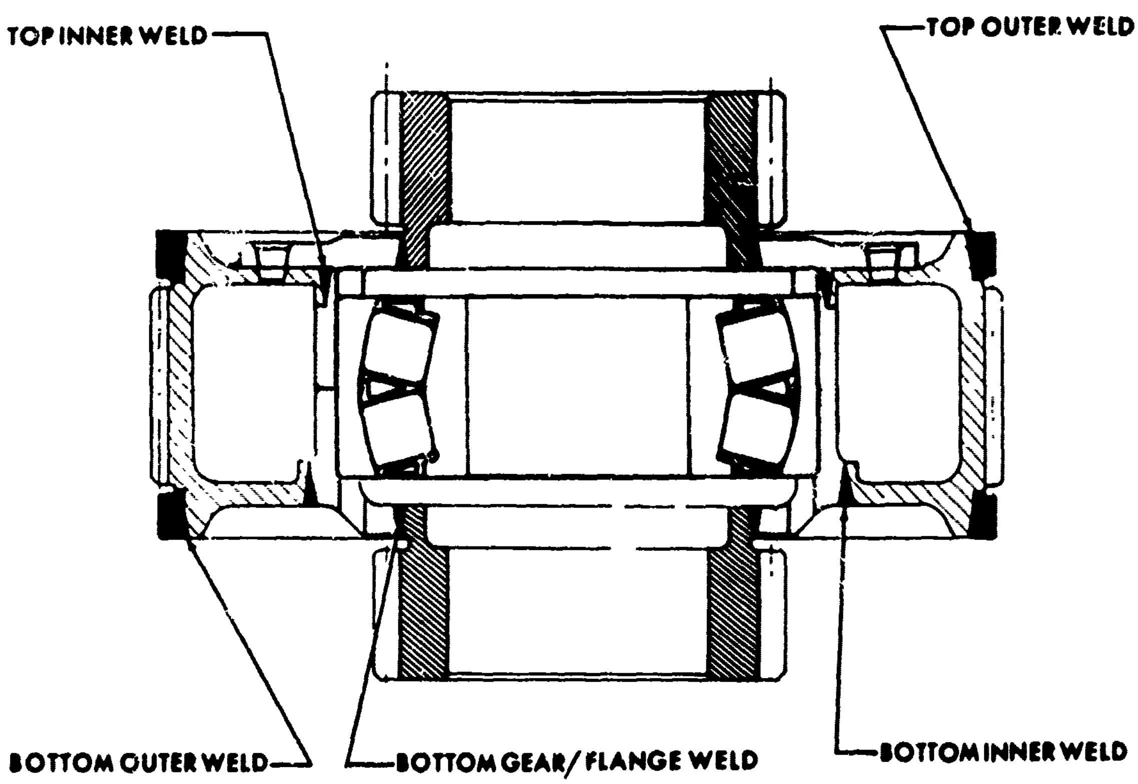

Figure 50. Electron-Beam-Weld Locations, Second-Row Gear

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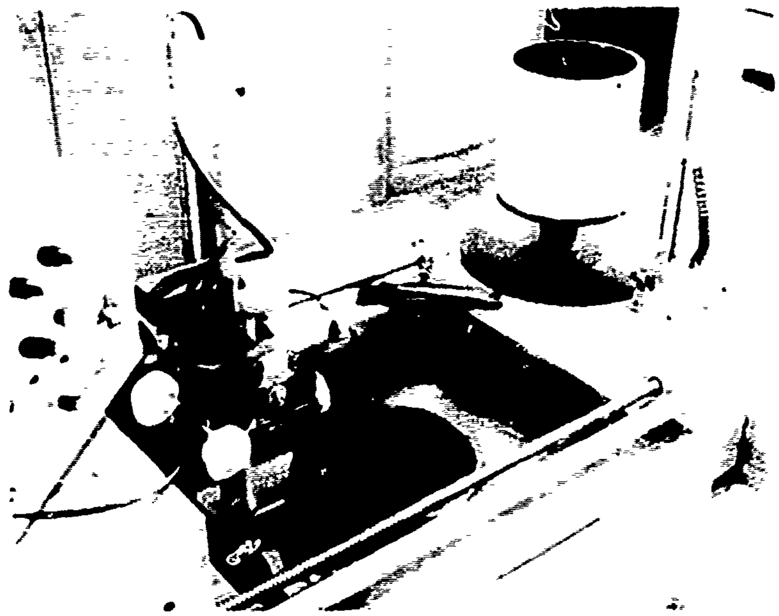

Figure 51. Ultrasonic Inspection Equipment

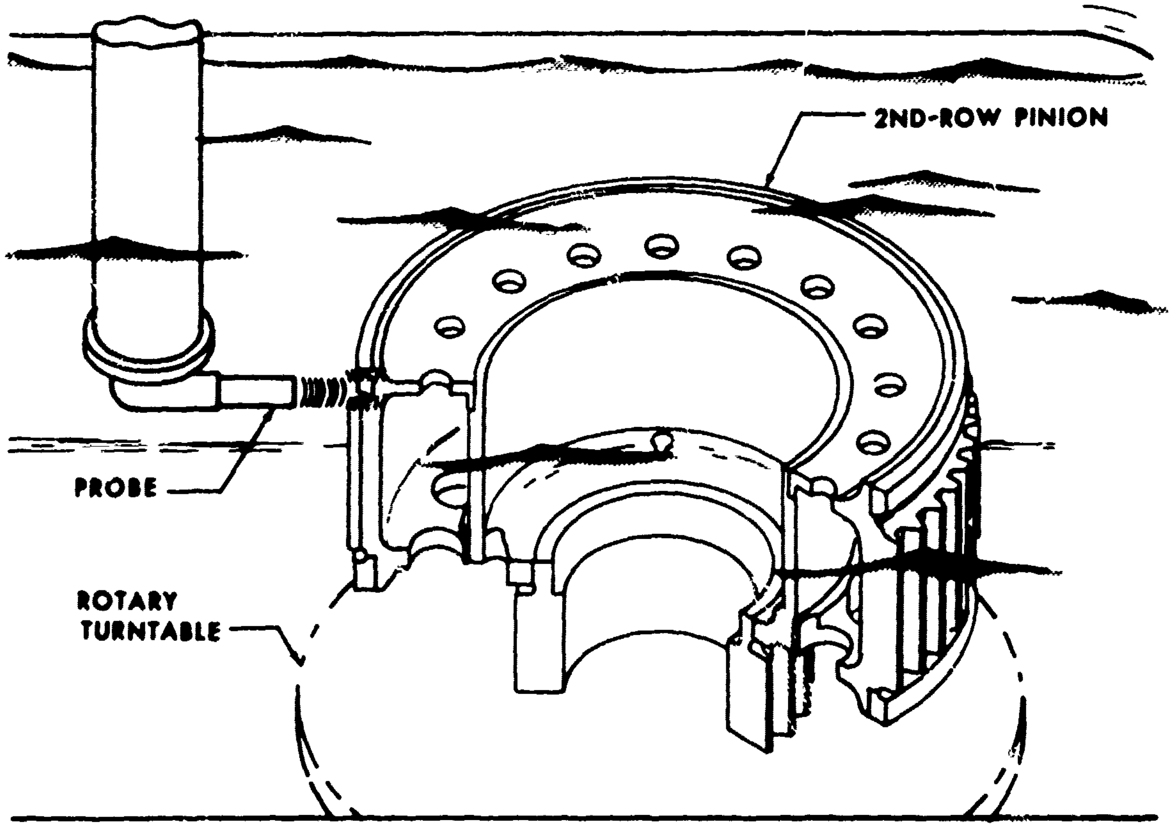

Figure 52. Ultrasonic Inspection Schematic

Figures 53 and 54 depict the C-scans of the second-row gear roller welds before and after testing. The degradation can be seen in the lower roller welds of serial numbers 45, 59, 60, 63, 65 and 71. Also, slight degradation is visible in the upper roller welds of serial numbers 59 and 65. The C-scans are recorded on an 8.0-inch-diameter drum; the weld diameter is 9.03 inches. Thus, the indication depicted on the C-scans is slightly smaller than the actual crack in the part. To determine the nature and cause of the indication, the lower roller of second-row gear serial number 63 was partially removed to reveal a fractured zone 1.0 inch long by 0.22 inch wide. Figure 55 shows the fractured zone which was revealed by locating the zone from the C-scan and machining the case-hardened roller with a solid carbide endmill.

Metallurgical examination of the fractured surface revealed that the crack originated at the interface of coarse granular structure and refined grain structure. This material transition zone is between the weld melt and heat affected zone. Multiple origins could be witnessed which propagated along grain boundaries. This, and the findings that Fe304 (an iron oxide compound) in this coarse granular structure, indicates that the crack originated prior to the application of black oxide (Dulite). This mildly corrosion protective treatment is applied after completion of fabrication of the gear and after final inspection by immersing the gear in a bath of equal parts of sodium nitrate and sodium nitrite. A detailed report of a fractographic analysis of the fracture is given in Appendix A. An investigation into the effect of dynamic loading on the cracks in these roller welds, as conducted in a ground test facility, is reported in "Crack Propagation Tests".

GREASE-LUBRICATED TAIL AND INTERMEDIATE GEARBOXES

No problems were encountered with the grease-lubricated tail and intermediate gearboxes throughout the tiedown test program, and no maintenance was required. These gearboxes, modified for grease lubrication, were being tested in accordance with Contract DAAJ02-73-C-0005 for the U. S. Army Air Mobility Research and Development Laboratory.

Test Data

The bearing temperatures for various powers, including maximum recorded temperatures, are listed in Table 26 corrected to a 15°C standard day. The temperature limit of 145°C was never reached, the highest observed temperature being 113°C on the tail gearbox input inner bearing. One characteristic noted was the time-dependent variation of the temperatures at a steady power level, as much as ±5°C. This characteristic of grease-lubricated bearings has been observed in previous testing.

The overall maximum vibration levels for the two vibration pickups on the tail gearbox and the intermediate gearbox (as presented in Table 23) were higher than expected, and since vibration monitoring was being considered as a possible failure detection method, an investigation was conducted into the characteristics of the vibrations. The vibration signals were subjected to a spectrum analysis, and the resulting plots are shown in Figures 56 and 57. The identifiable frequencies of interest are labeled in these figures. Intermediate gearbox spectrums were obtained early in the program and near the end, Figure 56. The plots show that a change occurred in both the character and the amplitude of the vibration as the test progressed. This change was also observed on oscillograph records as a change in waveform. No firm explanation for the change is offered since little experience has been gained in the measurement of gearbox spectrums on an operating helicopter, and none at all on grease-lubricated gearboxes. It is apparent that further work is required before vibration measurement and analysis may be used as a failure detection method. The spectrums presented here could be interpreted as indicating a deterioration of the intermediate gearbox, while in fact the postest inspection showed no discrepancy or indication of significant deterioration.

Spectrums for the two pickups on the tail gearbox are shown for reference in Figure 57. These spectrums were taken only once during the test. Oscillograph records again showed some variation in the amplitude and character of the waveforms from the tail gearbox pickups which did not appear to be dependent on test time.

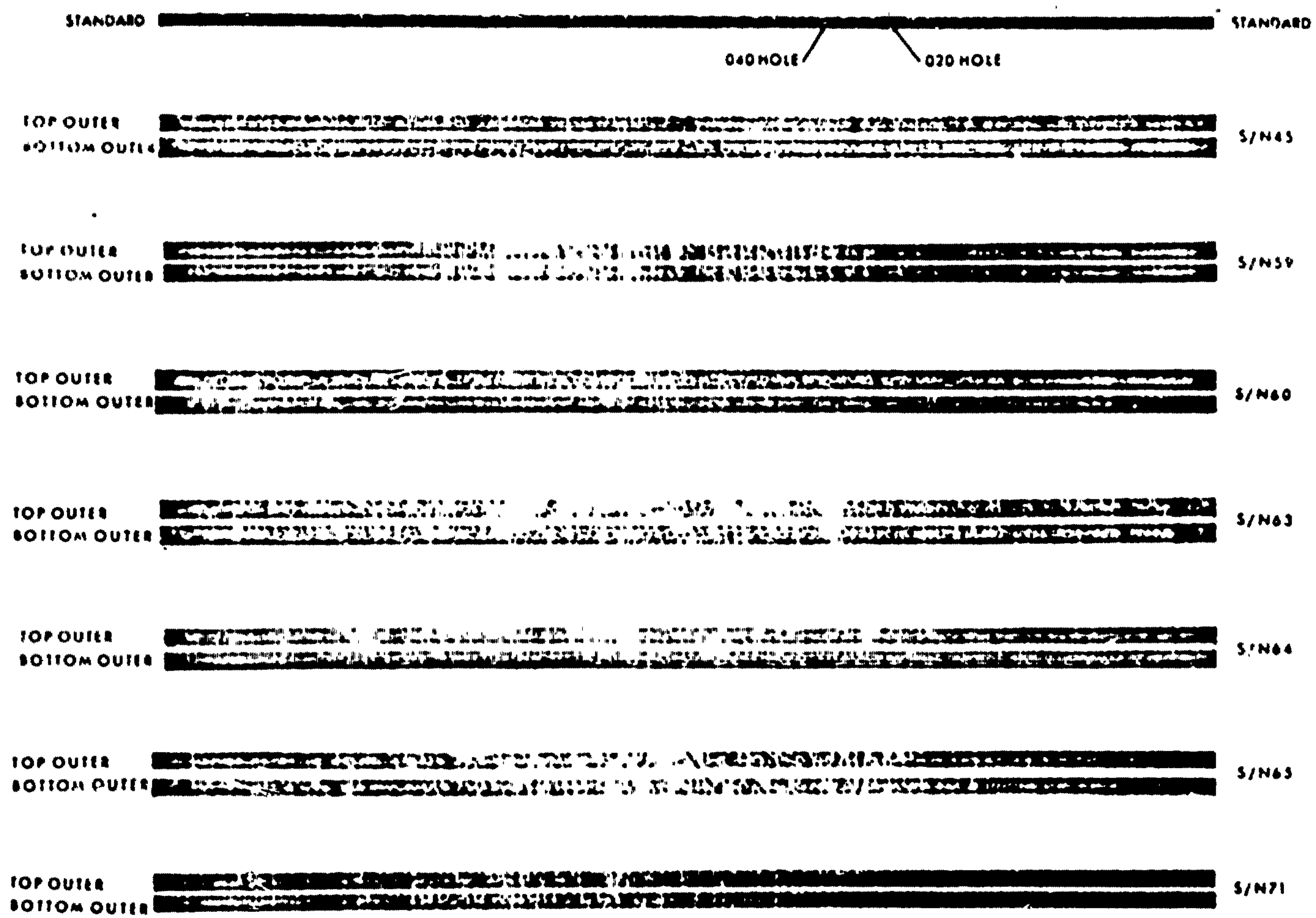

Figure 53. Ultrasonic Inspection C-Scans, Second-Row Gear Prior to Test

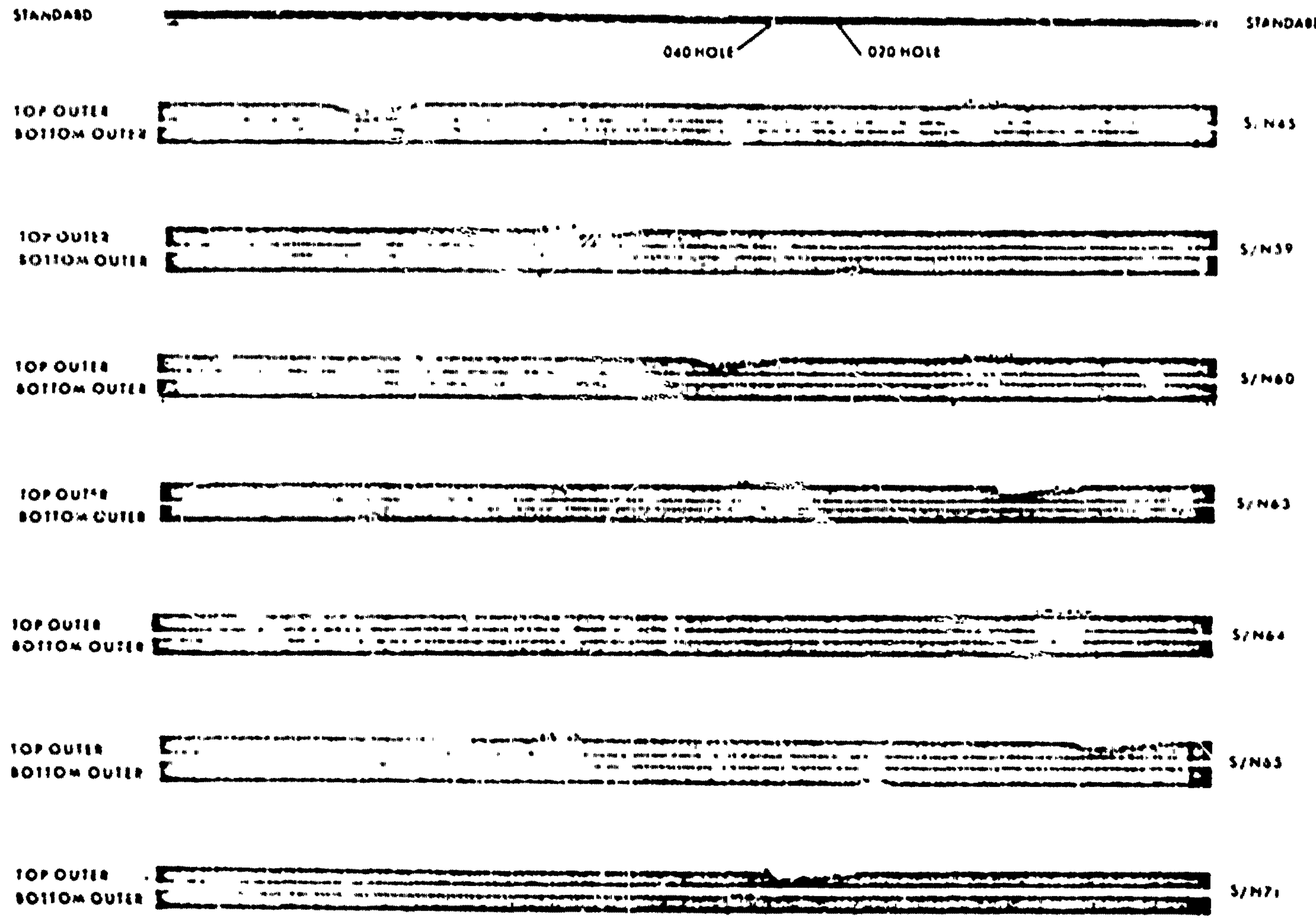

Figure 54. Ultrasonic Inspection C-Scans, Second-Row Gear After 50-Hour Test

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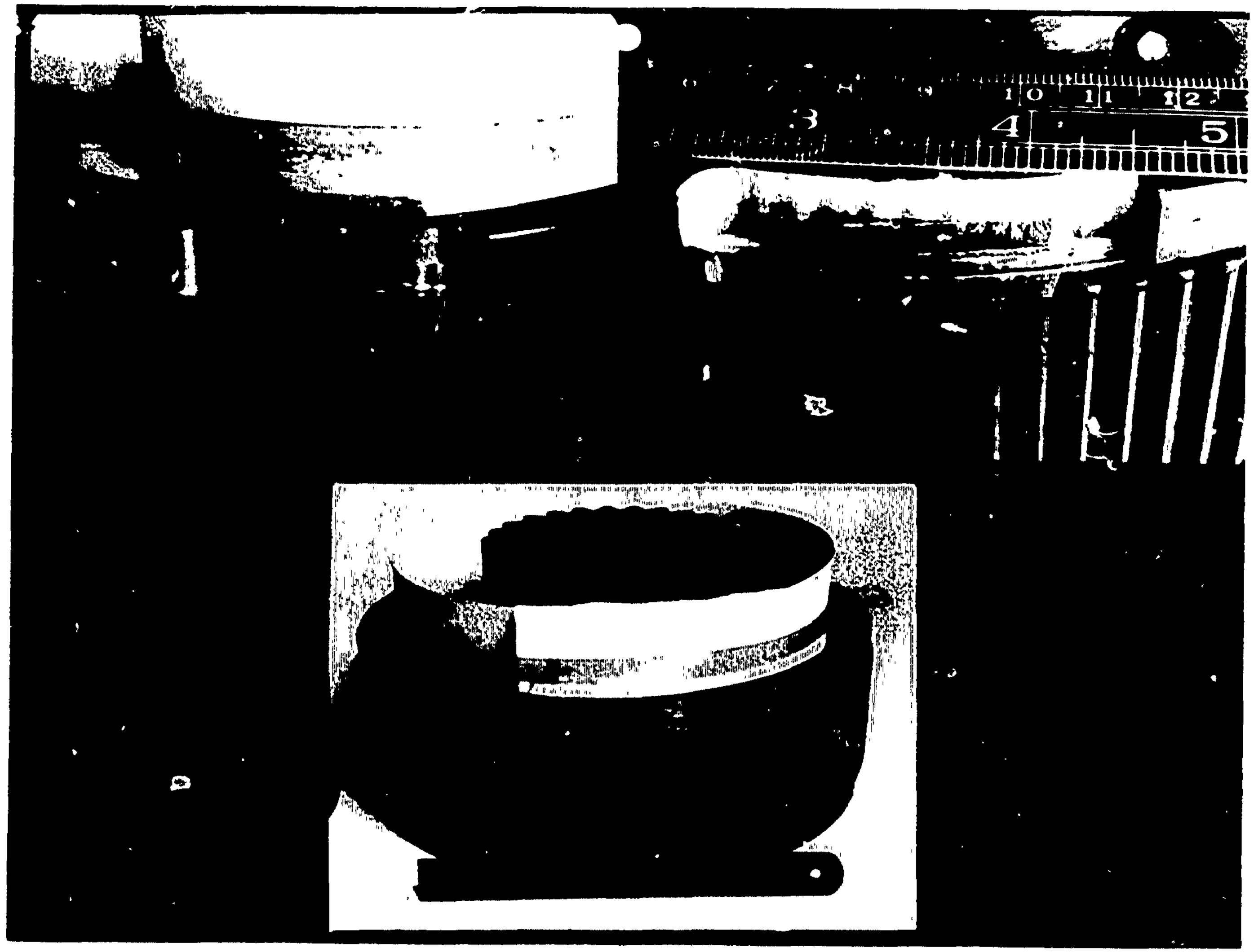

Figure 55. Fractured Roller Weld, Second-Row Gear

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TABLE 26. BEARING TEMPERATURES, INTERMEDIATE AND TAIL GEARBOXES

Bearing	Test Condition				Maximum Recorded
	60% NRP (180-218 hp)	80% NRP (266-355 hp)	100% NRP (266-339 hp)	Over-speed (232-342 hp)	
Tail Gearbox					
Input Outer	60	63	74	86	100
Input Inner	80	82	87	96	113
Output Outer	18	20	25	20	40
Output Middle	26	30	56	42	76
Output Inner	62	66	79	76	109
Intermediate Gearbox					
Input Center	40	46	46	54	78
Input Inner	38	50	51	63	85
Output Outer	21	26	54	48	75
Output Inner	31	38	49	44	85

NOTES:
1. Table entries are temperatures in °C.
2. All values except "Maximum Recorded" are corrected to a 15°C standard day.
3. Redline temperature, 145°C.
4. Maximum outside air temperature, 33°C.

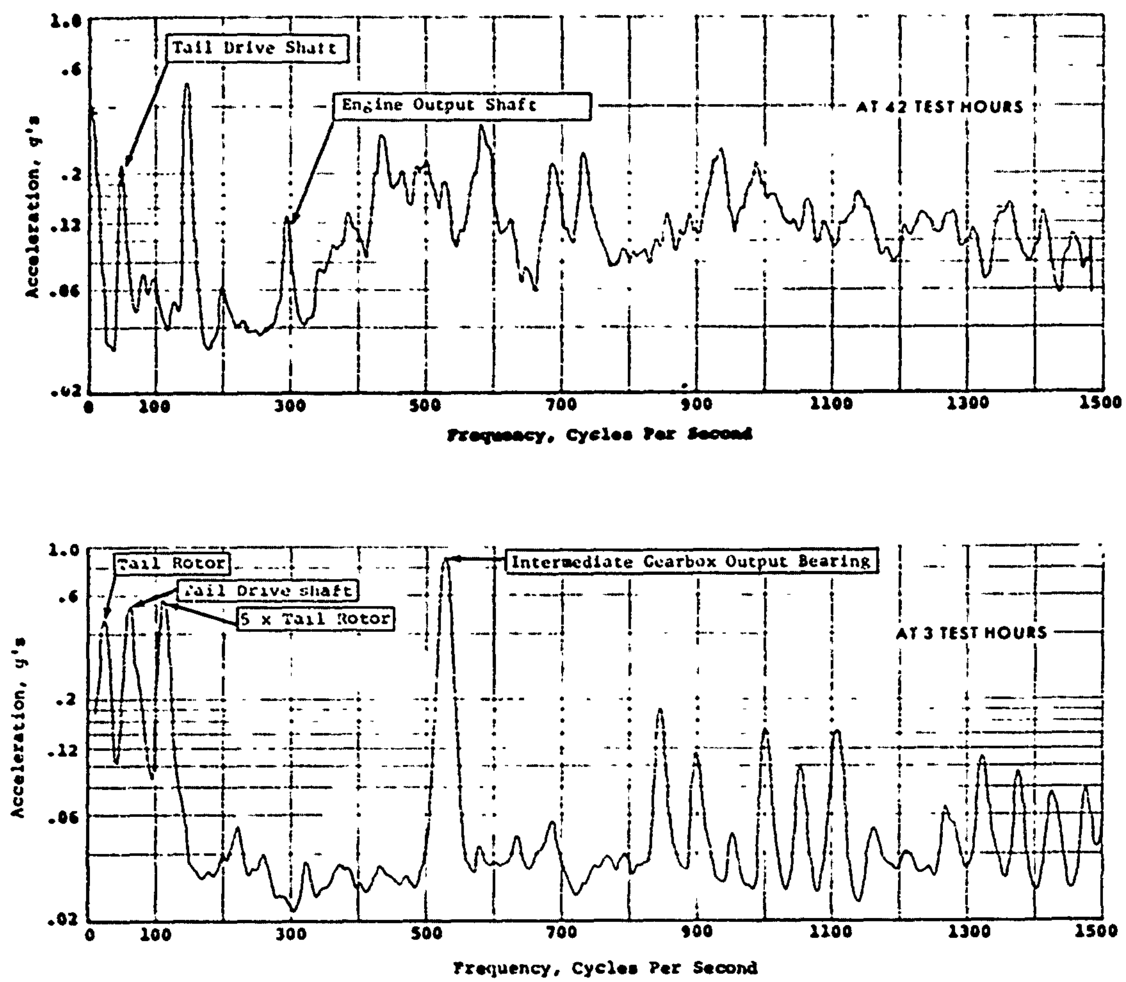

Figure 56. Vibration Spectrum, Intermediate Gearbox

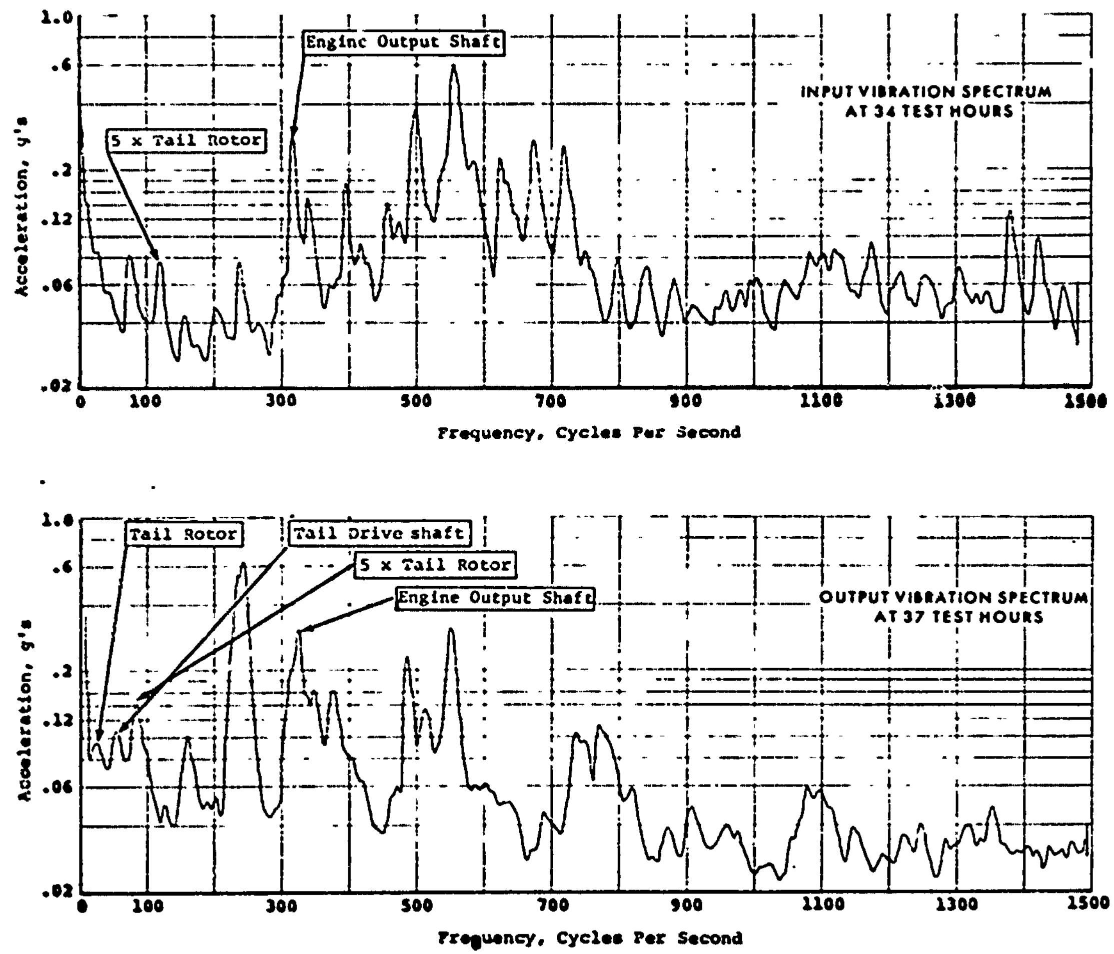

Figure 57. Vibration Spectrum, Tail Rotor Gearbox

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Posttest Inspection

After the 50-hour tiedown test was completed, the grease-lubricated intermediate and tail gearboxes were completely disassembled and visually inspected. The results of this inspection are presented below.

The MIL-G-83363 (USAF) grease lubricant in the intermediate gearbox showed no change in color or consistency from the as-new condition. A substantial amount of grease was retained in the gear mesh area as shown in Figure 58, and all gear teeth were coated with a film of lubricant. The gear teeth had a smooth, polished finish with no evidence of scoring or other surface distress. All bearings were in excellent condition with no evidence of surface distress or thermal damage. The bearing races and rolling elements all retained an ample film of lubricant. The gearbox lip seals evidenced no detectable wear or deterioration of the elastomer.

The grease in the tail gearbox exhibited a slight darkening with no detectable change in consistency. As in the intermediate gearbox, a substantial amount of lubricant was retained in the gear mesh area. The gearbox is shown with the input housing removed in Figure 59. The gear teeth also showed a film of grease. The teeth evidenced slight scoring as shown. This scoring is not considered to be a serious defect in light of the power levels at which the gearbox was operated.

The input and output gear shafts were magnetic particle inspected, and no crack indications were detected. The bearings were in good condition and showed substantial retained lubricant with no surface damage. The pitch control bearing showed some lubricant staining as well as a general darkening of the grease, but the rolling contact surfaces evidenced no distress. Both the input and output seals were in good condition with no detectable wear or elastomer deterioration.

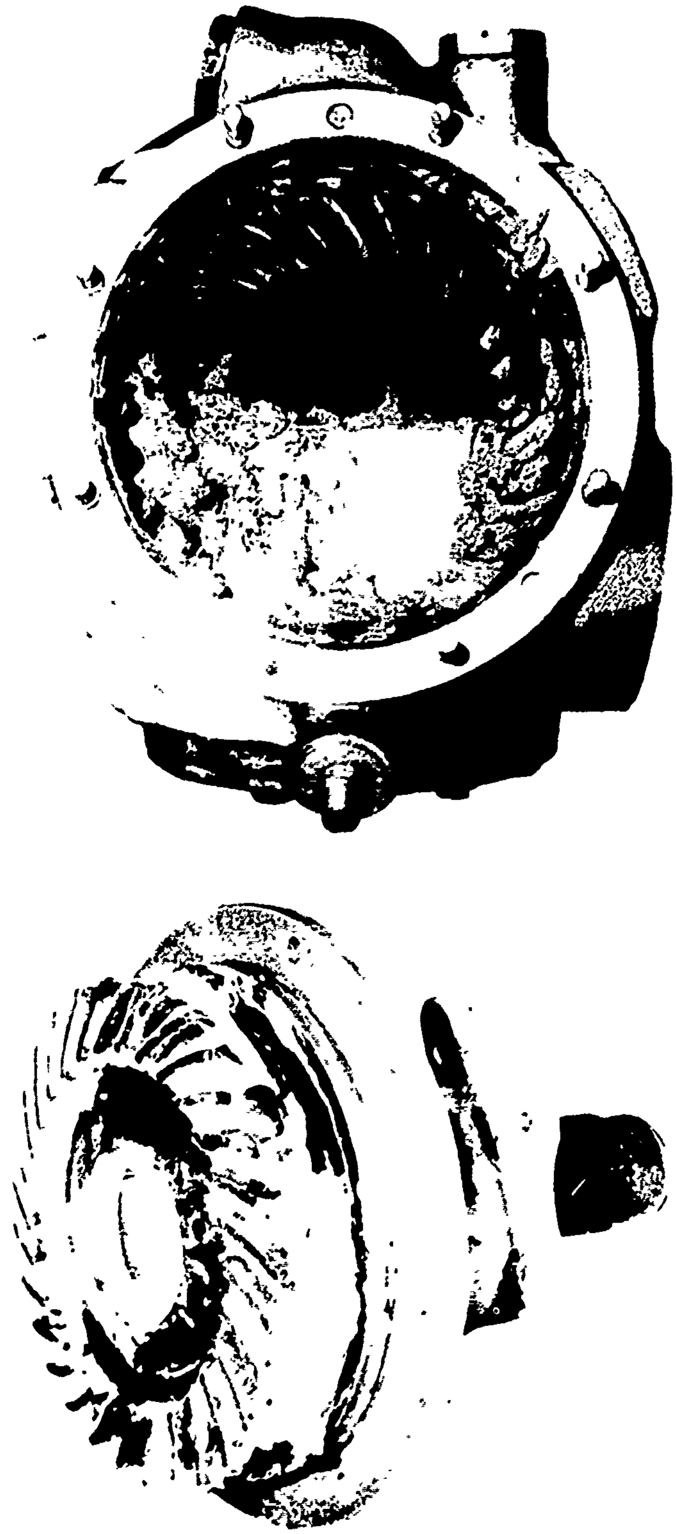


Figure 58. Posttest Inspection, Grease-Lubricated Intermediate Gearbox

Figure 59. Posttest Inspection, Grease-Lubricated Tail Gearbox

CONTROL SYSTEM

No problems or any evidence of binding, interference, deflections, or buckling was found when both hydraulic systems were on (normal operation). All measured control system loads were found to be very low and typical of tiedown operations. Table 27 presents the maximum loads observed with both hydraulic systems on.

TABLE 27. CONTROL LOADS SURVEY

Gage Location	Maximum Load (lb)	Test Condition
Rotating Scissors	31± 79	100% NRP Forward Cyclic
Rotating Pushrod	375±125	100% NRP Forward Cyclic
Stationary Scissors	13± 25	100% NRP Neutral Controls
Stationary Star No. 1	188±250	Overspeed Neutral Controls
Stationary Star No. 2	312±125	100% NRP Neutral Controls
Stationary Star No. 3	188±312	100% NRP Forward Cyclic
No. 1 Servo Input Rod	±120	Overspeed Neutral Controls
No. 2 Servo Input Rod	249	Overspeed Neutral Controls
No. 3 Servo Input Rod	160	Primary Servos Off

Note: The limiting load for the control system was that specified for the alpha-one bellcrank bracket of ±1900 lb.

In tests with one hydraulic system off, the following was found:

Auxiliary Hydraulic System Off

The control force measured at the cyclic stick grip increased from approximately 1 pound to 16 pounds when the auxiliary hydraulic system was turned off. The force increase was due to the frictional drag of the inoperative auxiliary servo and the friction of the control system between the auxiliary and primary servos. These control forces are considered to be unacceptable for normal flight operations in the event of an auxiliary hydraulic system failure.

Primary Hydraulic System Off

Turning off the primary hydraulic system while under power resulted in a loss of main rotor torque, blades out of track, and a one-per-rev aircraft oscillation. Early in the program, this power loss was up to 300 hp at high power levels. An investigation of the problem at the end of the program showed a loss of up to 600 hp when the primary servos were turned off at main rotor power level of 1,700 hp. The blades-out-of-track condition was observed to be 6-8 inches, and a strong one-per-rev vibration was experienced. Due to the severity of the condition, tests at higher power levels were not attempted.

Further investigations were conducted to resolve the problem. Four possible contributors were found: control system stiffness, main rotor blade pitching moments, alpha-one coupling wear and main rotor damper timing.

In normal operation, the primary servos provide a hard point in the control system just below the rotor head. When these servos are off, acting only as mechanical links, the spring rate presented to the swashplate is reduced significantly since the next hard point in the system is at the auxiliary servo. The addition of the analog mixer system to this aircraft has reduced the system spring rate from that of standard S-61 helicopters, where operation with primary servos off is avoided but not prohibited.

The main rotor blades on the test aircraft were units that had had many hours of service, had a wide range of serial numbers and had a history of repairs. Following the tiedown test these blades were subjected to dynamic blade balance on the Sikorsky blade balance test stand. It was found that a divergence of blade pitching moment characteristics occurred at high power levels. This difference in moments among blades resulted in an out-of-track condition when the swashplate assembly was not held rigidly, as when the primary servos were off. The soft control system can allow the swashplate to deflect in a one-per-rev motion, which appears as an out-of-track.

The alpha-one couplings, which replaced the rotating pushrods, incorporated Teflon bushings which are subject to wear and deformation. The resulting slop can exaggerate the out-of-track condition produced by the soft control system and blade pitching moment differences. At the conclusion of the tiedown tests, this slop was found to be excessive.

Posttest inspection and testing revealed variations in damping rate among dampers. This can also contribute to a one-per-rev vibration on the aircraft.

AIRFRAME

Relatively few airframe problems were encountered during the test program. Of primary concern was the transmission mount area, which had been a problem area with standard S-61 helicopters. High stresses were measured, and a crack did occur in this area (Station 290) near the end of the tiedown program.

Stress Survey

The maximum stress and load levels observed in the test program with the conditions at which they occurred are presented in Table 28. Also shown in the table are typical maximum S-61 flight stresses.

Transmission mount stresses are higher than maximum flight levels at each of the four stations monitored. At the transmission rear support gage, for example, 32,000 ± 3,500 psi was measured on tiedown, while 25,000 ± 3,000 psi is a typical maximum flight level. Some of the tail pylon measurements are also above flight levels. The primary reason for the increase is the higher power level obtained on tiedown (up to 3,000 main rotor hp) as opposed to the S-61 flight conditions (up to 2,000 main rotor hp). In addition, the distribution of loads within the airframe on tiedown produces an acceleration of loading not found in flight.

Vibration Levels

Maximum vibration levels with the condition at which they occurred are shown in Table 23. The vibration pickups located on the gearboxes also serve as airframe vibration pickups. Primary attention was directed to the low-frequency components of these measurements. Although some of the vibration levels are excessive, they are typical of tiedown vibration levels, where the operation at high power close to the ground produces an unnatural environment for the aircraft.

At 46 test hours, a station 290 crack occurred adjacent to the transmission mount strain gage on the riveted cap strip of the transmission transverse rear frame. The test aircraft had not been updated to the latest strap configuration in this area. The crack originated at a drilled rivet hole in the cap strip. The crack was stop-drilled and no further progression was noted.

TABLE 28. AIRFRAME STRESS SURVEY

Gage Location	Maximum Stress (psi)	Test Condition	Typical Maximum S-61 Flight Test Data (psi)
Transmission Mounts			
Rear Frame - Right	28,000+3,000	100% NRP Forward Cyclic	-
Rear Frame - Lower	32,000±3,500	100% NRP Left Cyclic	15,000+4,000
Rear Frame - Inboard	27,500±2,500	100% NRP Left Cyclic	25,000±3,000
Forward Attachment	25,620±2,000	100% NRP Right Cyclic	-
Tail Pylon			
Tail Pylon	5,700+1,240	100% NRP Left Pedal	10,500+3,300
Tail Pylon Hinge	11,400±2,900	100% NRP Left Pedal	8,300±4,900
Tail Pylon Hinge	8,300±1,240	100% NRP Left Pedal	9,100±2,400
Tail Pylon Hinge	11,900±1,240	100% NRP Left Pedal	10,700±2,200
Stabilizer Attachment	1,600±2,560	100% NRP Left Pedal	7,700±5,800
Stabilizer Attachment	4,810	100% NRP All	8,150±6,600
Tail Cone 6 o'clock position	2,060	100% NRP Left Pedal	4,000± 900
Tail Cone 4 o'clock position	2,060	100% NRP Forward Cyclic	4,200± 650
Tail Cone 3 o'clock position	6,190	100% NRP Neutral Controls	4,700± 750
Tail Cone 1 o'clock position	2,060	100% NRP All	350±2,100

After 38.5 test hours, ꞓ skin crack occurred adjacent ɔ a longitudinal stringer on the starboard topside of the ↑ il cone. The tail cone skin of a tıed-down S-61 type aircraft is ɔrone to "oil-canning", and skin cracks of this sort are not considered serious. The crack was stop-drilled and patched. No further progression was noted.

After 46 test hours, a main blade tip cap was found cracked at the transition area from heavy to light gage construction; the cracked unit was replaced.

CRACK PROPAGATION TEST, SECOND-ROW GEARS

Upon completion of the 50-hour tiedown test, the sun gear, first-row pinion and second-row gears of the roller gear unit were subjected to ultrasonic inspection in order to verify the integrity of the electron beam welds. It was found that six of the seven second-row gears showed degradation in the lower roller weld when compared to ultrasonic C-scans obtained prior to testing. Examination of the C-scans shows that degradation occurred along a line of voids similar to those associated with weld pullout. The similarity of the degraded area in only the lower roller weld prompted reexamination; however, this only confirmed previous results. Removal of the degraded area by machining revealed that initial fracture probably resulted from excessive residual stresses due to welding and that fatigue cycling propagated the size of the initial fracture zone.

Investigation of the welding procedures used revealed the use of identical welding schedules for both top and lower roller welds. The only discrepancy in procedure was that a 24-hour time lag occurred between welding of the lower roller and stress relieving immediately after welding of the top roller. This agrees with the fractographic results documented in Appendix A that residual stresses due to welding resulted in initial fracture.

ROLLER GEAR BACK-TO-BACK TEST FACILITY

Further testing was conducted in order to determine the fatigue crack propagation rate of the remaining six second-row gears. This was conducted in a back-to-back test rig which subjects two roller gear units to 3,000 hp at 203 rpm. This facility, depicted in Figure 60, shows two roller gear units supported from the spherical roller bearings in the second-row pinions. The test roller gear is the upper unit; the slave, the lower unit. The input sheave, driven from a 150-hp electric motor, transmits power through the torque tube drive shaft to the upper and lower torque plates, whereby load is statically applied to both roller gear units. Drive is then transmitted to the upper roller gear unit via the quill shaft. The ring gear output of this unit drives the ring gear of the slave and is the input for the lower roller gear unit. The lower quill shaft closes the torque loop by its attachment to the torque tube drive shaft. The torque from each unit is reacted through the spherical bearings of the second-row gears to the stationary posts and hence into the framework of the test rig. Torque is measured and monitored through slip rings from the calibrated strain-gaged torque tube drive shaft.

Lubrication of each roller gear unit is by methods similar to that used in the aircraft gearbox. Lube oil is fed into a manifold which directs oil to the spherical bearings in the second-row gears. A separate feed line supplies oil to seven probe jets which direct oil to the outgoing mesh of each gear and roller contact. A central membrane separates the two roller gear units and prevents any debris from the upper unit contaminating the lower unit. The exiting lube oil from each chamber passes through separate, continually monitoring, magnetic chip detectors before being combined at a facility oil pump.

CRACK PROPAGATION TESTS

The test unit was comprised of the roller gear unit components utilized during the 50-hour tiedown test. A replacement second-row gear was substituted for the dissected gear.

A 100-hour high-load test was proposed with ultrasonic inspections being conducted at 15, 25 and 100 test hours. After 15 test hours, at a steady 2,640 hp at 203 rpm, ultrasonic inspection revealed no significant increase in the size of the weld fracture zone. Similarly, after a further 25 hours of testing at 3,000 hp, no increase in flaw size was noticeable.

At 57 hours 45 minutes test time, the test was terminated. Initial indication came from the chip detector for the upper (test) roller gear unit. Examination of the particles indicated the necessity to remove the unit for further examination, whereupon second-row gear serial number 64 was found to be fractured.

CRACK PROPAGATION TEST RESULTS

Examples of the ultrasonic C-scan results at 15 and 40 test hours and at termination of testing are shown in Figure 61. When compared to the C-scans taken prior to the commencement of the crack propagation test, it can be seen that crack propagation was negligible.

Examination of second-row gear serial number 64 revealed that it was fractured into two pieces, as seen from Figure 62. Initial fracture occurred at the bearing bore weld; when this area fractured, secondary fracture occurred in the area of the outer roller weld due to the large leverage load from the unsupported ring gear mesh forces. Extensive pounding on the fracture surface prevented location of the initial fracture origin, but sufficient evidence was visible to show that fracture progressed from voids at the root of the weld to the inside bearing bore, Figure 63. The secondary fracture originated from the stress concentration notch at the roller location face.

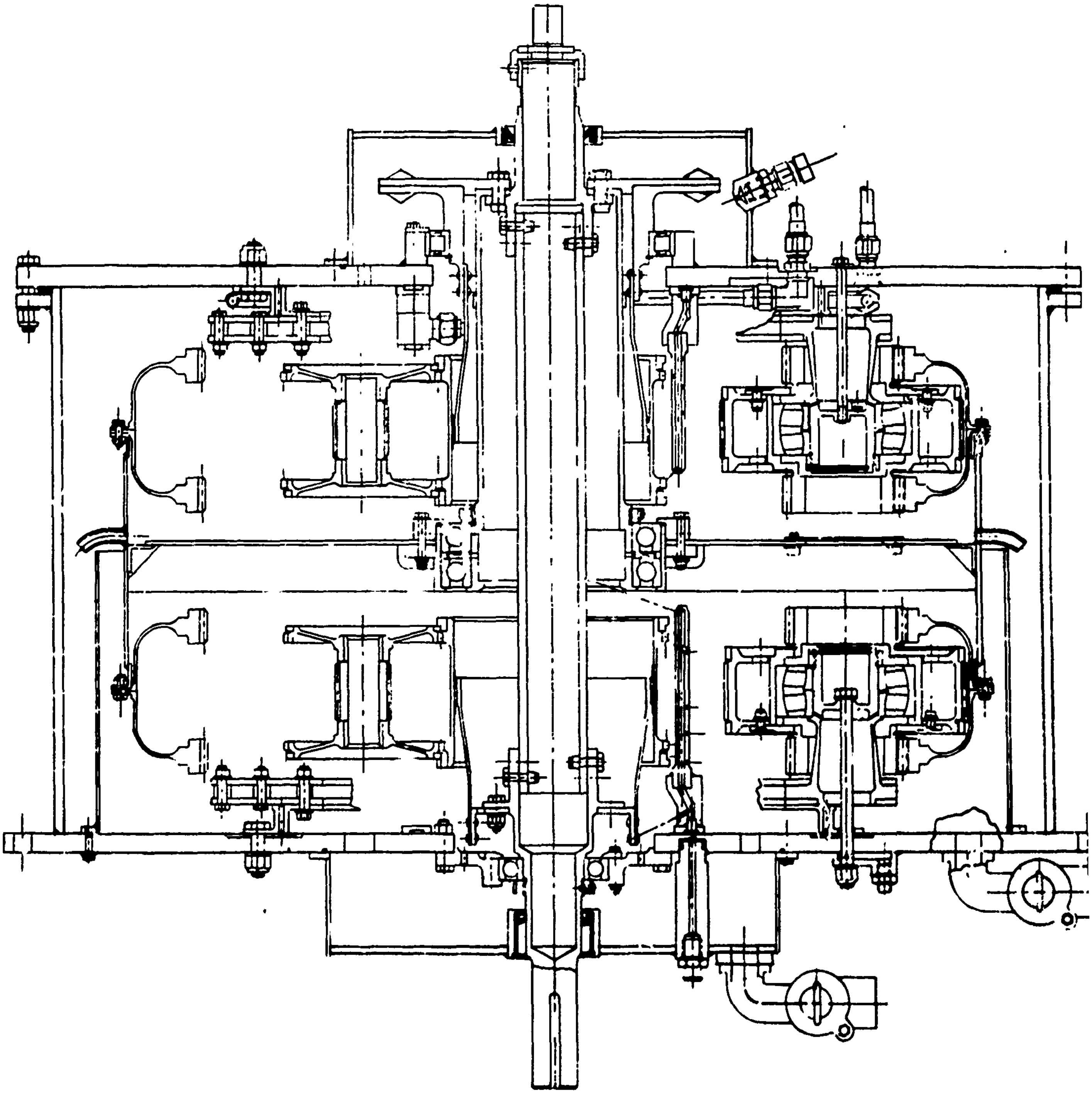
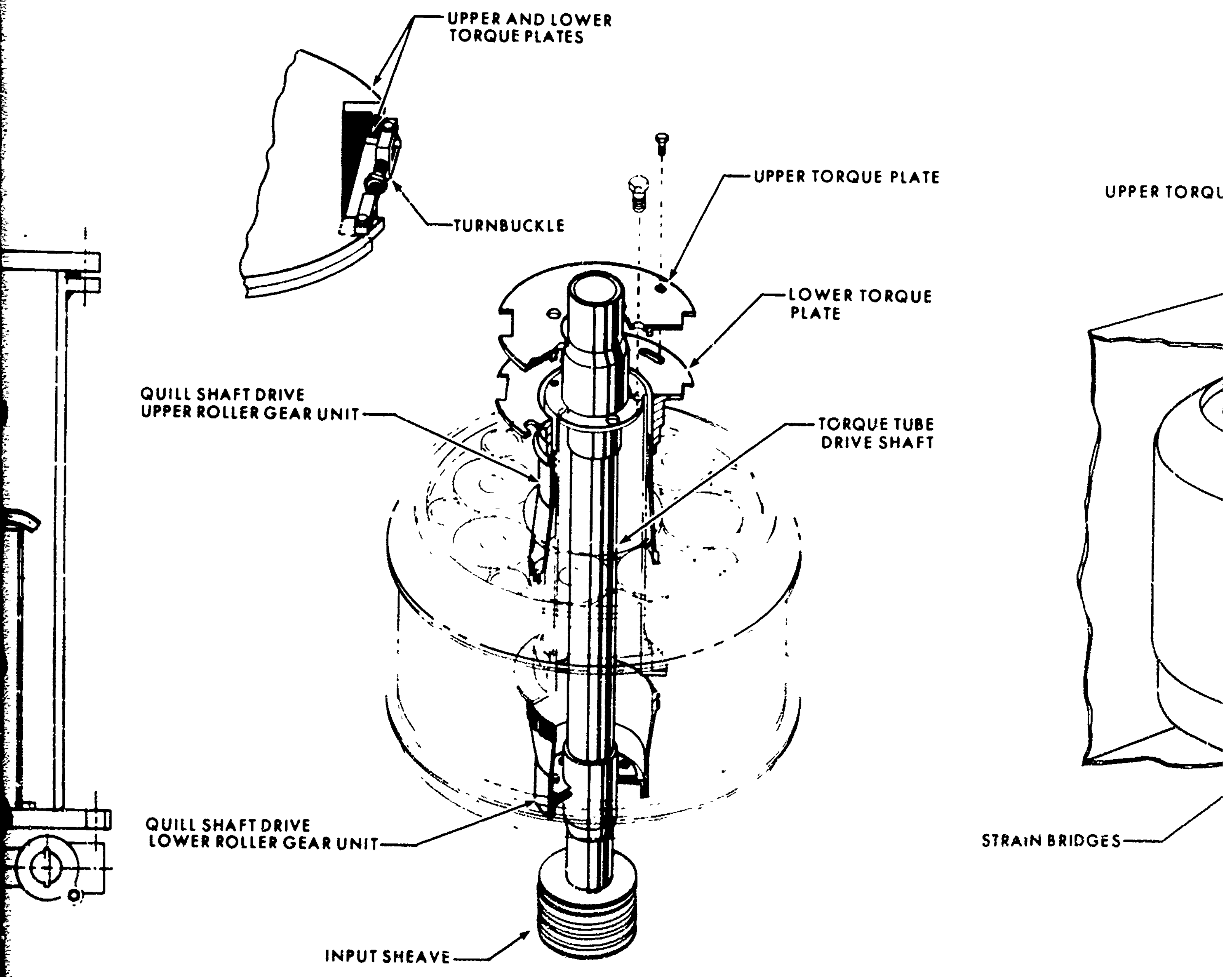
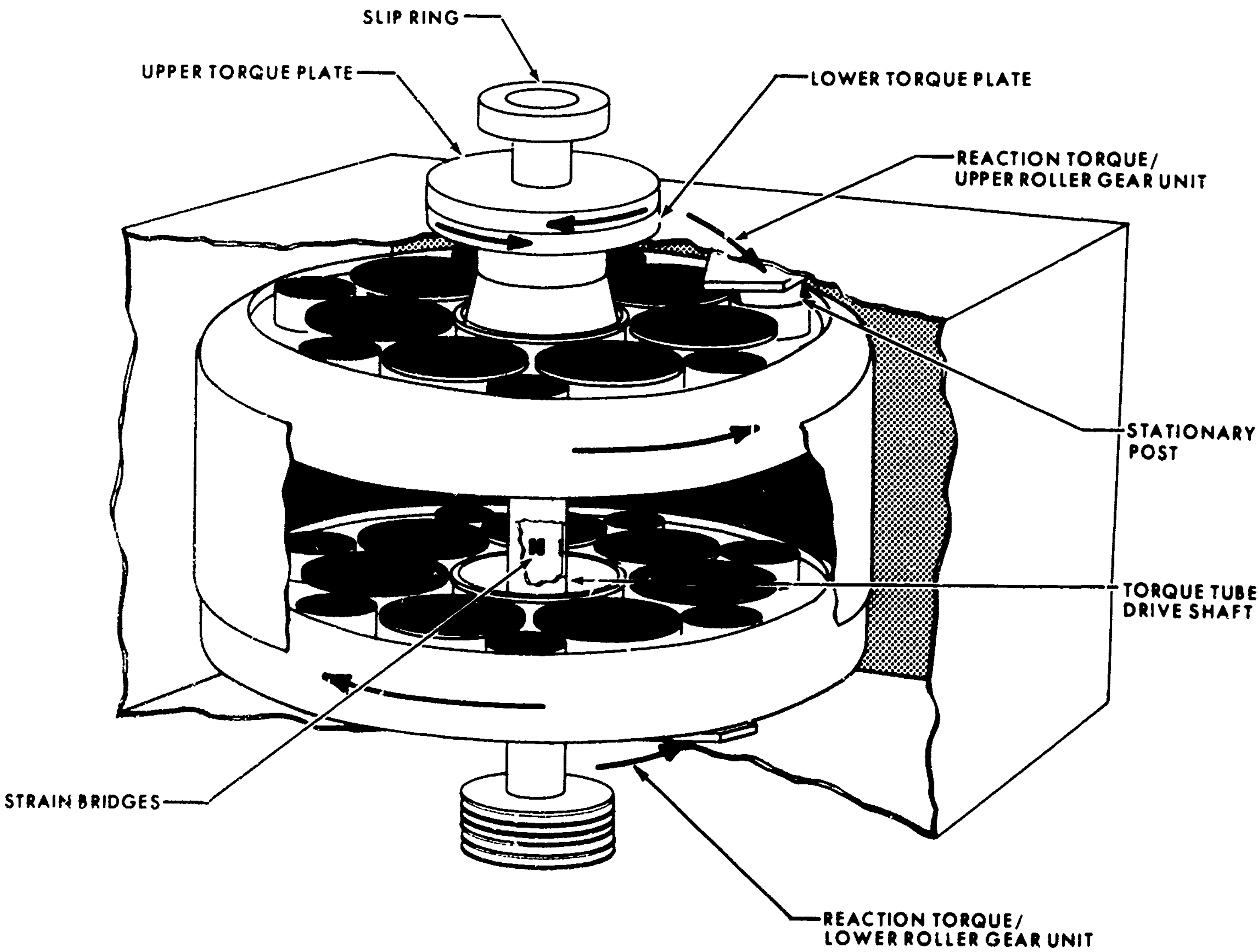


Figure 60. Back-to-Back Roller Gear Test Rig



UPPER AND LOWER TORQUE PLATES
TURNBUCKLE
UPPER TORQUE PLATE
LOWER TORQUE PLATE
QUILL SHAFT DRIVE UPPER ROLLER GEAR UNIT
TORQUE TUBE DRIVE SHAFT
QUILL SHAFT DRIVE LOWER ROLLER GEAR UNIT
INPUT SHEAVE
UPPER TORQU
STRAIN BRIDGES

B


SLIP RING
UPPER TORQUE PLATE
LOWER TORQUE PLATE
REACTION TORQUE/
UPPER ROLLER GEAR UNIT
STATIONARY
POST
TORQUE TUBE
DRIVE SHAFT
STRAIN BRIDGES
REACTION TORQUE/
LOWER ROLLER GEAR UNIT

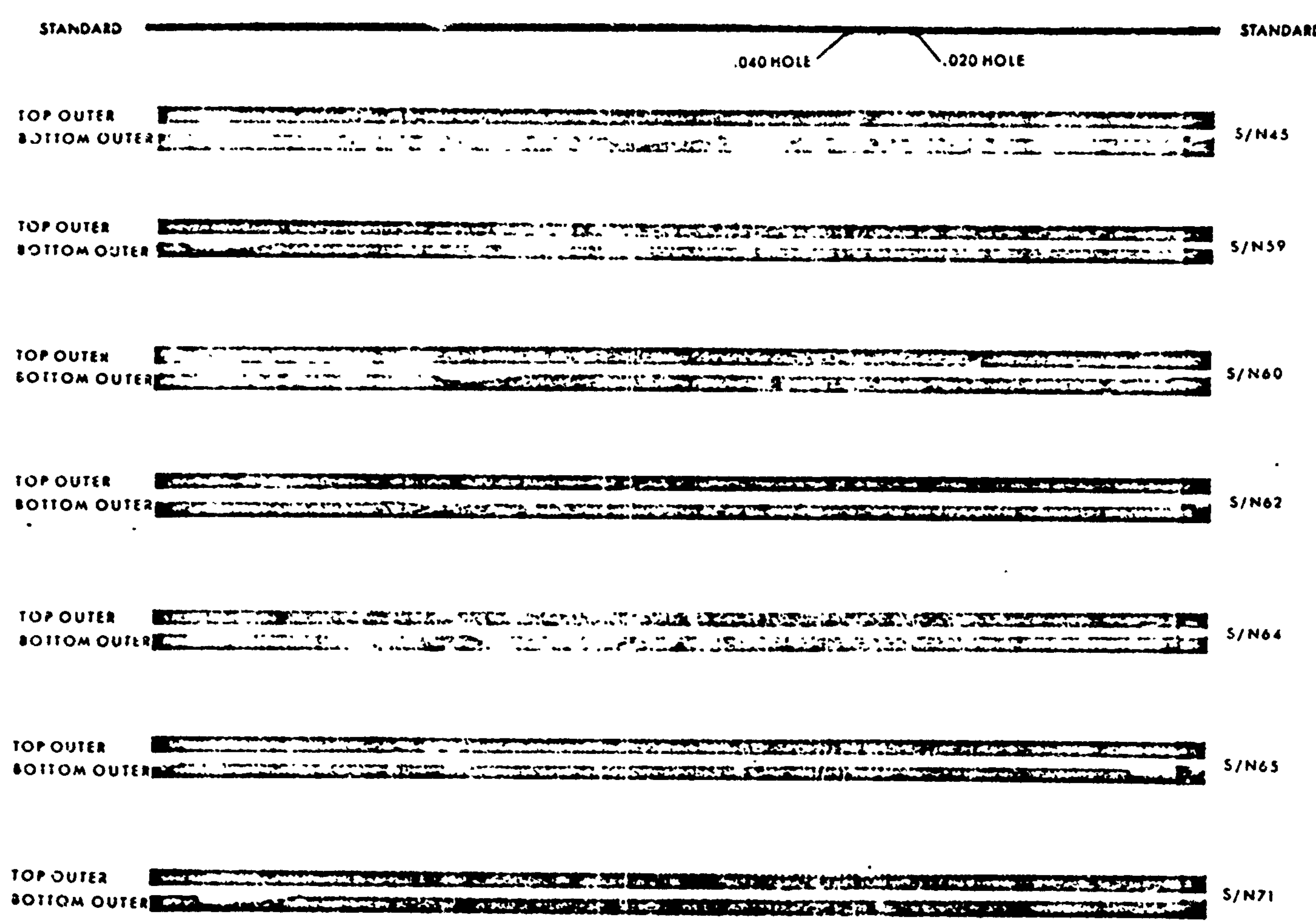


Figure 61. Ultrasonic Inspection C-Scans, Crack Propagation Test

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Magnetic particle inspection of the roller gear components revealed cracks in the bearing bores of five second-row pinions. These fractures were in the area adjacent to the root of the weld, where the initial fracture of serial number 64 occurred.

The wear patterns on the gears was, except for some slight debris damage, excellent. The rollers themselves showed no damage.

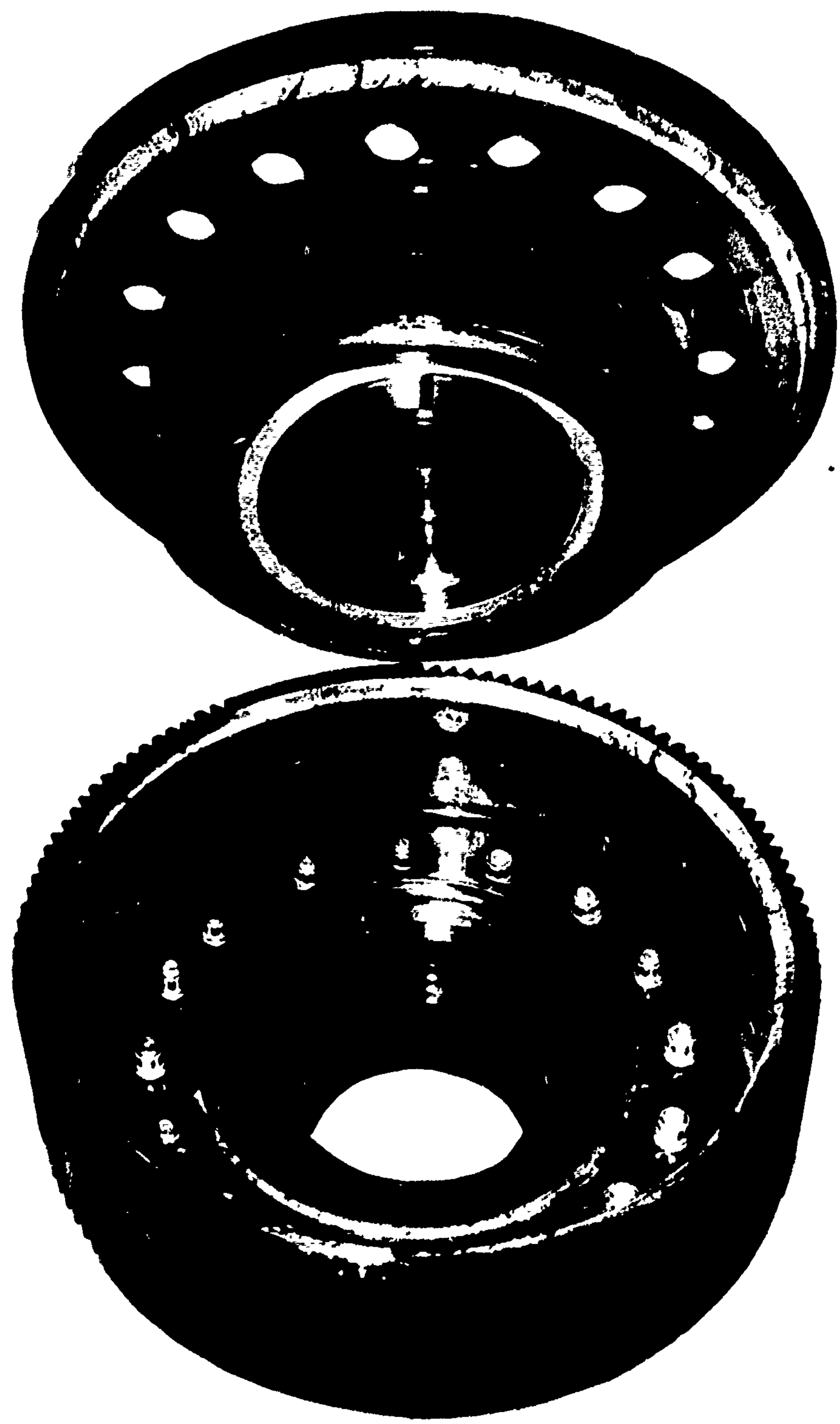

Figure 62. Fractured Second-Row Gear, S/N 62

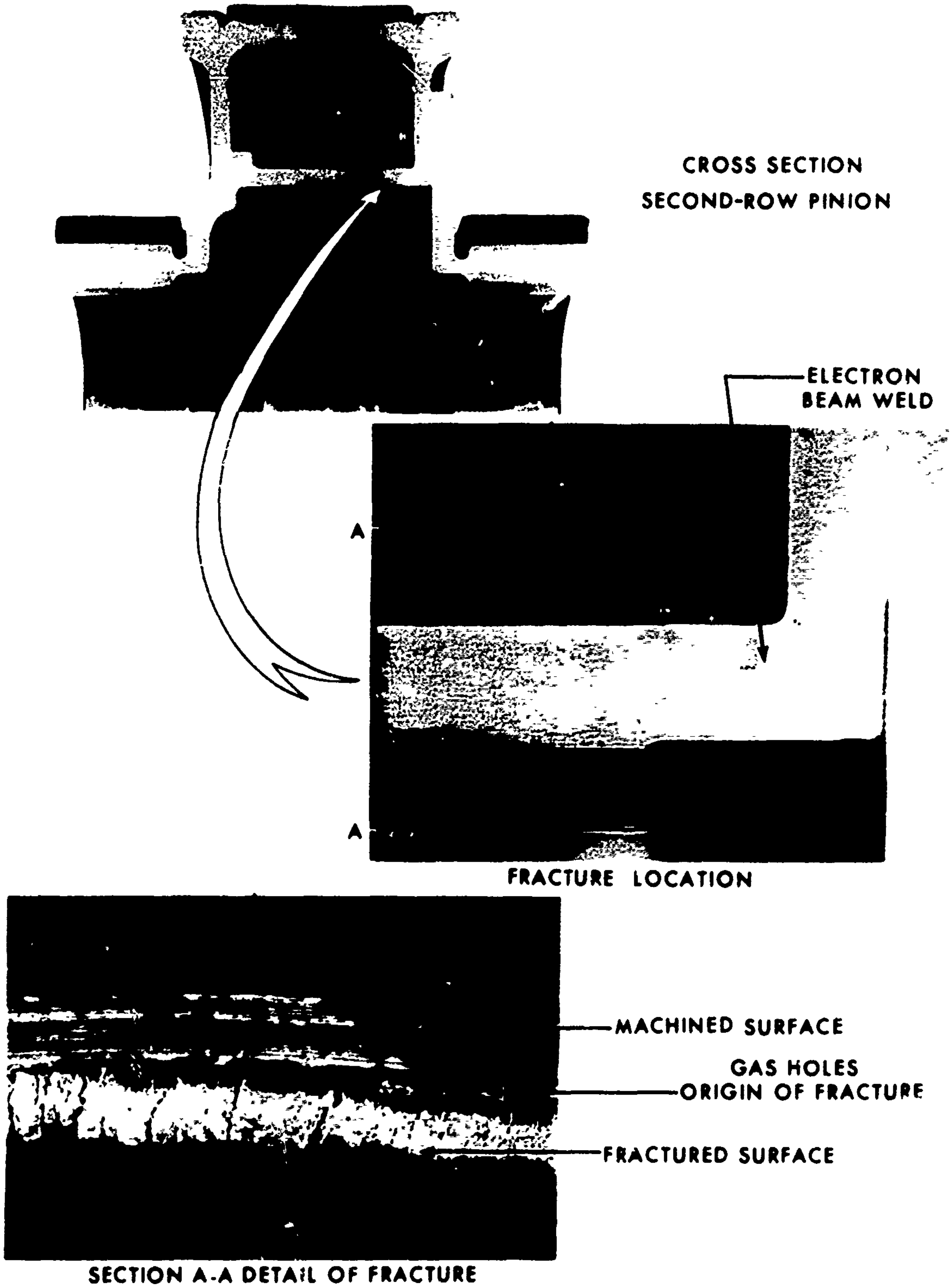

Figure 63. Primary Fracture, Second-Row Gear, S/N 62

CONCLUSIONS

The aircraft tiedown test program showed that the roller gear unit can operate within the fatigue environment of a helicopter main transmission. The roller gear unit gave no cause for concern throughout the 50-hour tiedown program.

It is concluded that:

1. The roller gear concept provides excellent load sharing and gear load distribution as evident from the gear wear patterns. During this test program, the roller gear unit transmitted an excess of 3,000 hp. The gears and pinion rollers showed no evidence of surface deterioration except for two adjacent first-row pinion rollers. This was attributable to insufficient blending of the roller crown on the mating second-row gear roller.

2. The spherical bearings and cantilevered posts allowed the roller gear unit to be self-aligning and provided the flexibility to accommodate the angular displacement of the post when reacting torque. The spherical bearings in the second-row gears withstood a high degree of tolerance to debris. Fretted particles from the second-row gear spacers, used to provide bearing axial clamp-up, were continually being washed through the bearing without noticeable damage to the bearing element surfaces. Because of the successful operation of these bearings and the cantilevered bearing post design, these concepts have been incorporated in advanced geared planetary transmission units designed subsequently.

3. The input bevel gears designed with a modified contact ratio of 2.63, successfully operated above pitch-line velocities of 29,500 ft/min. This test advanced the state of the art of bevel gears and supporting ball stack bearing design. The ramp roller freewheel units evidenced slight malfunction on overspeed conditions. This is an occasional occurrence with experimental outer-race driving units and can be overcome by increasing the roller preload force.

4. Balancing of the high-speed shafts at 3,000 rpm proved to be unsatisfactory. By balancing at 11,000 rpm, operation vibration limits were within aircraft acceptable limits. The torque monitoring system did not function correctly until the end of testing. Interface problems between vendor and aircraft equipment were not solved until near the end of testing, when insufficient test time remained to assess the accuracy of the system.

5. The second-row gear weld cracks showed the necessity to machine out voids associated with the weld root. A full penetrating weld, machined on the weld entrance and root faces, simplifies inspection and interpretations of ultrasonic inspection C-scan results.

6. Ultrasonic inspection monitoring of the cracked second-row roller gear welds showed that the crack had arrested and that load cycling crack propagation tests did not measurably increase the size of the defect. Fractographic analysis concluded that this fracture resulted from weakened grain boundaries due to residual stresses induced by the rapid heating and cooling cycle induced by electron beam welding. This was verified by investigation of the manufacturing process. It is now mandatory that all electron beam welding be immediately followed by a stress-relieving operation.

7. The fracture of the second-row gear which terminated the crack propagation test resulted from voids at the root of an electron-beam-welded joint. These fractures show the desirability of designing welded joints whereby weld entrance and weld roots can be machined to remove weld undercut and root splatter.

It is thus concluded that the roller gear transmission limitations were a result of weld joint design and manufacturing processes. The roller gear transmission proved to be a successful transmission system for the 50-hour tiedown test. With the correction of the aforementioned electron-beam-weld associated problems, the roller gear unit should operate successfully in the fatigue environment of a helicopter transmission. It is further concluded that the aircraft performance was satisfactory throughout the tiedown test and that:

8. The grease-lubricated tail and intermediate gearboxes performed satisfactorily.

9. The General Electric YT58-GE-16 engines operated satisfactorily. The degradation in performance was attributable to hot days and ingress of exhaust gases from turbulence created by rotor downwash and ground proximity.

10. The control system for the 120-degree servo spacing of the roller gear transmission proved to be less sensitive and stiffer than the standard S-61 type system for 90-degree servo spacing. This is largely attributable to the incorporation of the analog swashplate and the softness of the existing supporting structure within which the redesigned controls were installed.

RECOMMENDATIONS

1. It is recommended that the roller gear components be redesigned to eliminate "blind" electron beam welds and that testing of the roller gear unit alone continue in the ground test facility to evaluate the endurance characteristics of the roller gear transmission unit.

2. A major unknown in the electron beam welding of the roller gear components is the relationship between welding imperfections and structural performance. The defects should be characterized so that their influence on static and fatigue performance can be predicted.

3. Ultrasonic inspection proved to be a valuable tool in determining weld cleanliness; however, small voids (less than .010 inch) are not characterized. A means of determining the three-dimensional location and size of all defects in the weldment is required.

4. The effect of welding residual stresses on the fatigue and fracture behavior of weldments needs to be determined. The requirement for stress-relieving should be established.

5. Further investigation and testing of grease-lubricated gears and bearings are required. Means to monitor degradation of gears and bearings in a grease environment should be developed.

6. Further testing of the successfull high-speed input bevel gears and bearing system arrangement should continue. Future-generation engines may operate at 30,000 rpm; thus bevel gear systems offering a high reduction and redirection of power would be required to operate at pitchline velocities approaching 35,000 ft/min.

7. Further effort should be conducted in correlating the analytical studies of high-speed shafting with the actual aircraft system. Although significant advances have been made in analyzing flexible shaft responses, there are still factors which require further definition.

APPENDIX A

FRACTOGRAPHIC ANALYSIS

SECOND-ROW GEAR ROLLER FRACTURE

A fractographic analysis of the dissected second-row gear serial number 63 wherein degradation of the low roller weld occurred during the 50-hour tiedown test was conducted.

Optical inspection of the entire fracture surface revealed two apparently different fracture modes. The initial mode, located along the exit side of the weld, was discolored and appeared coarse and brittle. The more predominant fracture mode was mostly flat, and badly rubbed, with several coarse "clamshell" markings emanating from the discolored brittle zone, Figure A-1.

Replicas taken from this initial fracture zone exhibited distinct evidence of intergranular cracking. The fractured grain facets showed partial dimple formations indicative of a mechanical separation as opposed to separation by chemical dissolution.

Electron diffraction analysis of a black powdery material found on the initial fracture zone (none was detected on the remainder of the fracture) was identified as the same iron oxide (Fe_3O_4, ASTM Card No. 11-614) which coated the overall surface of the subject gear. The presence of this oxide on the initial fracture zone suggests that incipient cracks exited at the weld prior to the oxide-forming treatment of the gear.

Replicas taken from the more extensive, relatively flat portion of the fracture exhibited vague, closely spaced fatigue striations, characteristic of a low-stress, high-cycle fatigue fracture. Despite the poor definition of the fatigue striations, it appeared clear that the fatigue crack rate remained fairly constant.

Cross sections were made of two ends of one-half of the fracture interface to determine the extent of intergranular cracking and its precise location within the weld zone. As shown in the end views, intergranular cracking was nonuniform across the crack width, penetrating to a maximum depth of 750 microns at one end, and a minimum of a few grains at the other. Inspection of the cross sections at a lower magnification showed that the intergranular cracks developed at the interface of the coarse-grained melt zone and the finer-grained heat-affected zone.

A hardness traverse taken across this region revealed values of Rc38 for the melt and heat-affected zone, and Rc27 for the base metal.

It was concluded that:

1. Fracture initiated from the exit side of the weld, at the interface of the melt and heat-affected zones.

2. The mode of initial fracture was intergranular, probably resulting from weakened grain boundaries and excessive residual stresses due to welding.

3. Fatigue developed after the initial intergranular crack and propagated approximately 6.0 mm for a total of 160,000 load cycles.

4. The rate of fatigue propagation remained essentially the same at 0.037 micron per load cycle for the duration of the fatigue crack.

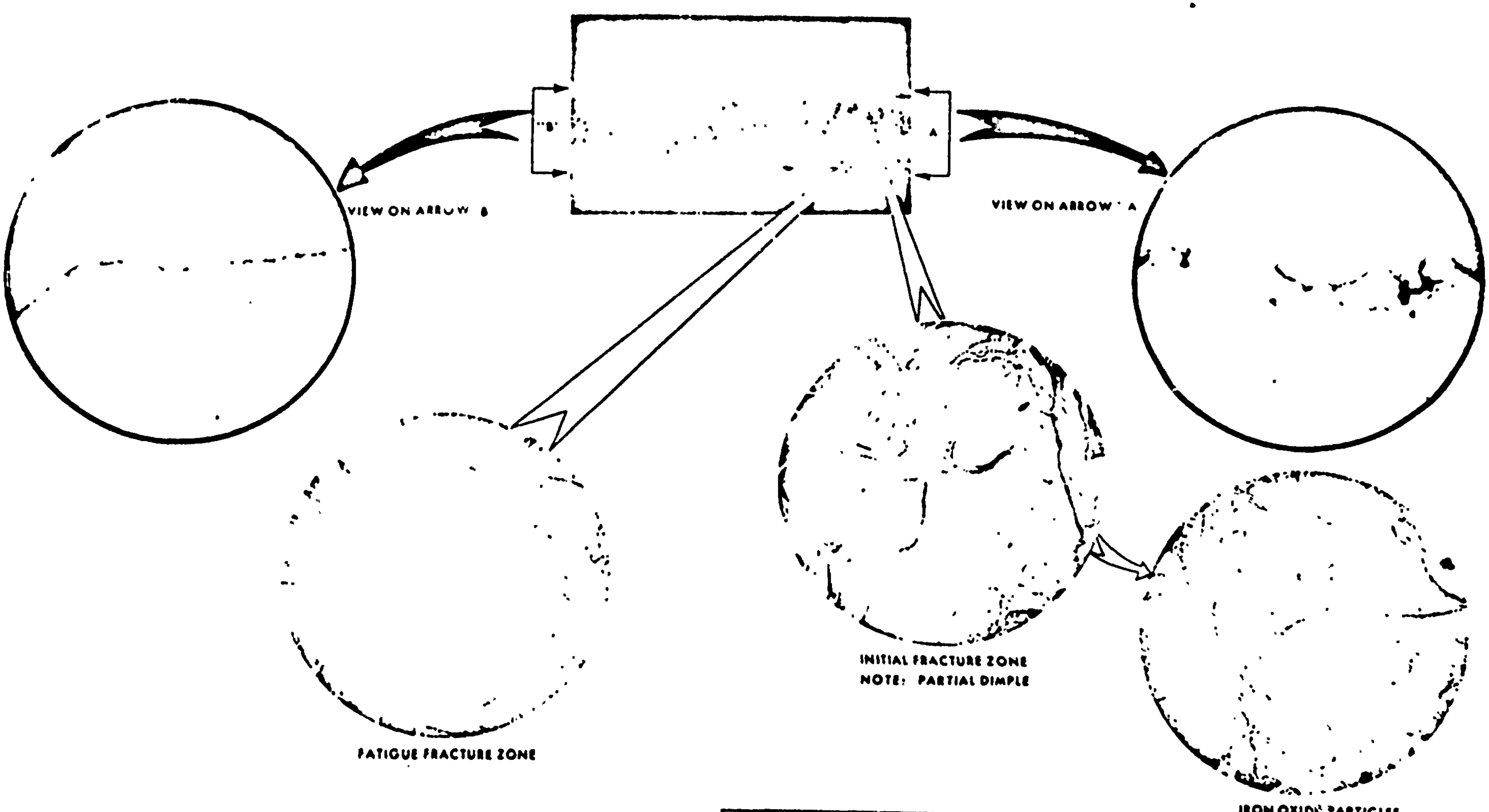

Figure A-1 - Second-Row Gear Lower Roller Weld Fracture